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NEOTECTONIC INVESTIGATIONS IN SOUTHERN ONTARIO: PRINCE EDWARD COUNTY - PHASE II

by

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NEOTECTONIC INVESTIGATIONS IN SOUTHERN ONTARIO
PRINCE EDWARD COUNTY - PHASE II

A report prepared by G.H. McFall and Ahmed Allam of the Ontario Geological Survey under contract to the Atomic Energy Control Board.

ABSTRACT

This report summarizes the preliminary results of geological and geophysical investigations and offshore side scan sonar surveys of the bedrock and unconsolidated sediments in Prince Edward County, souther Ontario, by the Ontario Geological Survey in 1989. Investigations were focused on deformations in the bedrock and the surficial deposits. Some of these deformations may be neotectonic in origin. Low magnitude seismicity in the Prince Edward County region appears to be spatially related to a major regional fault system that crosses Lake Ontario and consists of the seismically active Clarendon-Linden Fault System in New York State, the Picton-Napanee and Rideau Faults, the Frontenac-Sharbot Lake Terrane Boundary and the assumed Salmon River Fault in Ontario.

Detailed observations were made in the Long Point study area and the Mountain View and Picton Quarries. Bedrock structural features were documented, including: joints; normal, reverse and strike strip faults; brittle folds; and a Jurassic age ultramafic dyke.

Detailed refraction seismic surveys were conducted across a local fault and possible fold structures. Magnetic surveys, conducted in conjunction with the offshore side scan sonar surveys, documented large magnetic anomalies southeast of Point Petre and at the northeast end of Long Reach.

Side scan sonar surveys of the lake bottom to the east of Point Petre confirm the presence of pop-ups in that area of the lake bottom which is immediately adjacent to where pop-ups are observed on land. The pop-ups present in the lake bottom have similar orientations to those mapped in the study area.

RÉSUMÉ

Le présent rapport résume les résultats préliminaires de relevés géologiques et géophysiques et de sondages sous-marins au sonar à balayage latéral de l'assise rocheuse et des sédiments meubles faits par la Commission géologique de l'Ontario dans le comté de Prince Edward, dans le sud de l'Ontario, en 1989. Les relevés visaient principalement les déformations de l'assise rocheuse et des dépôts en surface dont certaines pourraient être d'origine néotectonique. Il semble que la séismicité de faible magnitude dans la région du comté de Prince Edward pourrait être associée à un système majeur de failles traversant le lac Ontario et

comprenant la faille active Clarendon-Linden dans l'État de New York, les failles Picton/Napanee et Rideau, la faille marginale Frontenac-Sharbot Lake et la faille présumée de Salmon River en Ontario.

Des observations détaillées ont été faites dans le cadre de l'étude de la région de Long Point et des carrières Mountain View et Picton. Les caractéristiques de la structure de l'assise rocheuse ont été documentées, y compris les joints, les failles normales, inverses et de décrochements, les plis fragiles et le dyke ultramafique du jurassique.

Des relevés détaillés de réfraction sismique d'une faille locale et des structures possibles de plis ont été faits. Les relevés magnétiques faits parallèlement aux relevés sous-marins ont permis de documenter d'importantes anomalies magnétiques au sud-est de Point Petre et à l'extrémité nord-est de Long Reach.

Les relevés au sonar du fond du lac à l'est de Point Petre confirment la présence de surrections dans la partie du lac adjacente à l'endroit où l'on peut observer les mêmes structures sur la terre ferme. Les surrections au fond du lac ont des orientations similaires à celles qui ont été relevées dans la région étudiée.

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PREFACE

Subsequent to the acceptance of this report, but prior to its publication, new, relevant information was acquired by the senior author, G.H. McFall. Because the review and publication process is so time consuming, it was deemed appropriate to introduce the new information in this preface, rather than to incorporate it into the text and repeat the entire review process. This information, gathered from the field as well as from the literature, shows that the Salmon River follows a major fault which cuts the Paleozoic rocks in southern Ontario.

The Salmon River Fault was described in the following manner by Liberty (1963): "A normal fault lies along Salmon River, its west side downthrown, about 100 feet. Detailed investigations indicate step-faulting and subsequent minor breaks in the strata. Movement along this fault is post-Blackriveran." Van Tyne (1975, p. 4), in discussing the Clarendon-Linden Fault in western New York State, wrote: "Chadwick saw that the rocks in the area were downthrown at least 100 feet to the west and felt that the western side had been 'shoved' northward relative to the eastern side, thus causing a downward displacement on the west...." Hutchinson, et al (1979, p. 210) stated that the Scotch Bonnet Rise, beneath Lake Ontario, is suspected of being an extension of the Clarendon-Linden and that "The Clarendon-Linden-Scotch Bonnet Rise structure is along the east flank of a magnetic minimum and along the west edge of a series of gravity maxima, both of which can be traced from west-central New York to the north shore of Lake Ontario." McFall and Allam (1989, p. 11 and Figures 6 & 7) described geophysical lineaments as coinciding "with bathymetric anomalies along a northeasterly trending line which connects the Clarendon-Linden fault to the Salmon River Fault...." From the above it seems very likely that the Clarendon-Linden fault continues into Ontario as the Salmon River Fault. Fakundiny (1978) stated that the Clarendon-Linden is seismically active.

At Kingsford, northwest of Napanee, a rock cut adjacent to the Salmon River features zones of cataclastic deformation, one of which displays sub-horizontal slickensides on secondary calcite. These zones are oriented 230°-85°, which is subparallel to the Salmon River at that location and strongly implies that the river follows a major fault. Green calcareous siltstone, exposed in the Salmon River northeast of Kingsford, is cut by many closely spaced fractures, indicative of fault zones. Also, slickensides, showing evidence of sinistral slip, occur on a large, 055°-oriented limestone face marking one of the valley walls of the Salmon River. Borehole data from Roblin show an approximately 30m drop in the Precambrian-Ordovician contact across the river.

Several lines of evidence indicate that the Salmon River lies within a major fault. The Salmon River Fault most likely represents the Ontario extension of the seismically active Clarendon-Linden Fault in New York State.

J.L. Wallach
Project Administrator
Atomic Energy Control Board

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NEOTECTONIC INVESTIGATIONS IN SOUTHERN ONTARIO
PRINCE EDWARD COUNTY STUDY - PHASE II

1.0 INTRODUCTION

1.1 INTRODUCTION

Detailed mapping of potential neotectonic bedrock features in the southern part of Prince Edward County was initiated in 1987 by the Ontario Geological Survey. Neotectonic research is being conducted by several agencies in Canada associated with the Multi Agency Group for Neotectonics in Eastern Canada (MAGNEC). Research being undertaken by other member agencies includes studies of Quaternary sediment deformation in the Charlevoix region of Quebec and the Miramichi region of New Brunswick.

Investigations by the Ontario Geological Survey have centred on the field identification of geological features which may indicate neotectonic activity, particularly features that have clearly occurred since deglaciation (approximately 12 000 years ago in the Prince Edward County area). This information, which is indicative of geologically recent structural instability, will

be submitted for consideration in revisions to the National Building Code scheduled for 1992. In the Paleozoic bedrock these features include recent movement on faults, pop-ups, and bedding plane slip.

Prince Edward County was chosen for study because it is transected by part of a major fault system, it is considered an area of little or no seismicity, the Quaternary and Recent deposits are generally relatively thin enabling bedrock features to be seen in plan view, recent and historic aerial photographs are available for the region, and the area is easily accessed.

Activities in 1989 concentrated on the southern part of Prince Edward County. In addition to detailed field mapping, activities included offshore side-scan sonar and magnetic surveys of the lake bottom, and detailed geophysical surveys over selected structural features within the Phase I study area. A number of informal names for both geographic locations and geological structures have been used throughout the report and are indicated by quotation marks.

1.2 LOCATION

Prince Edward County is an irregularly shaped peninsula which extends into the eastern part of Lake Ontario (Figures 1 and 2). The Phase II study areas are located in the southern and northeastern parts of the county (Figure 3).

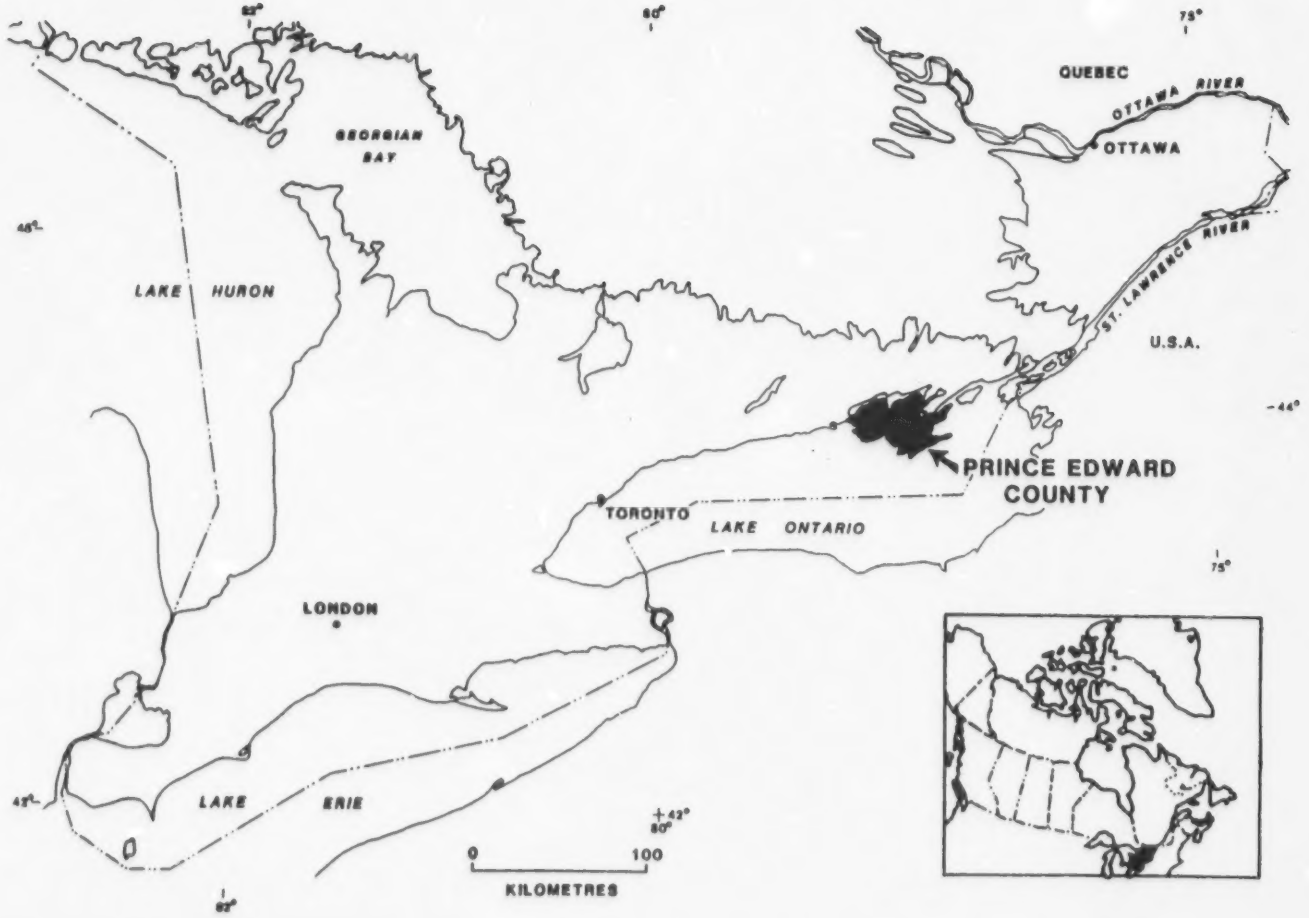

Figure 1: Location Map, Prince Edward County, southern Ontario.

Figure 2: Index map of Prince Edward County.

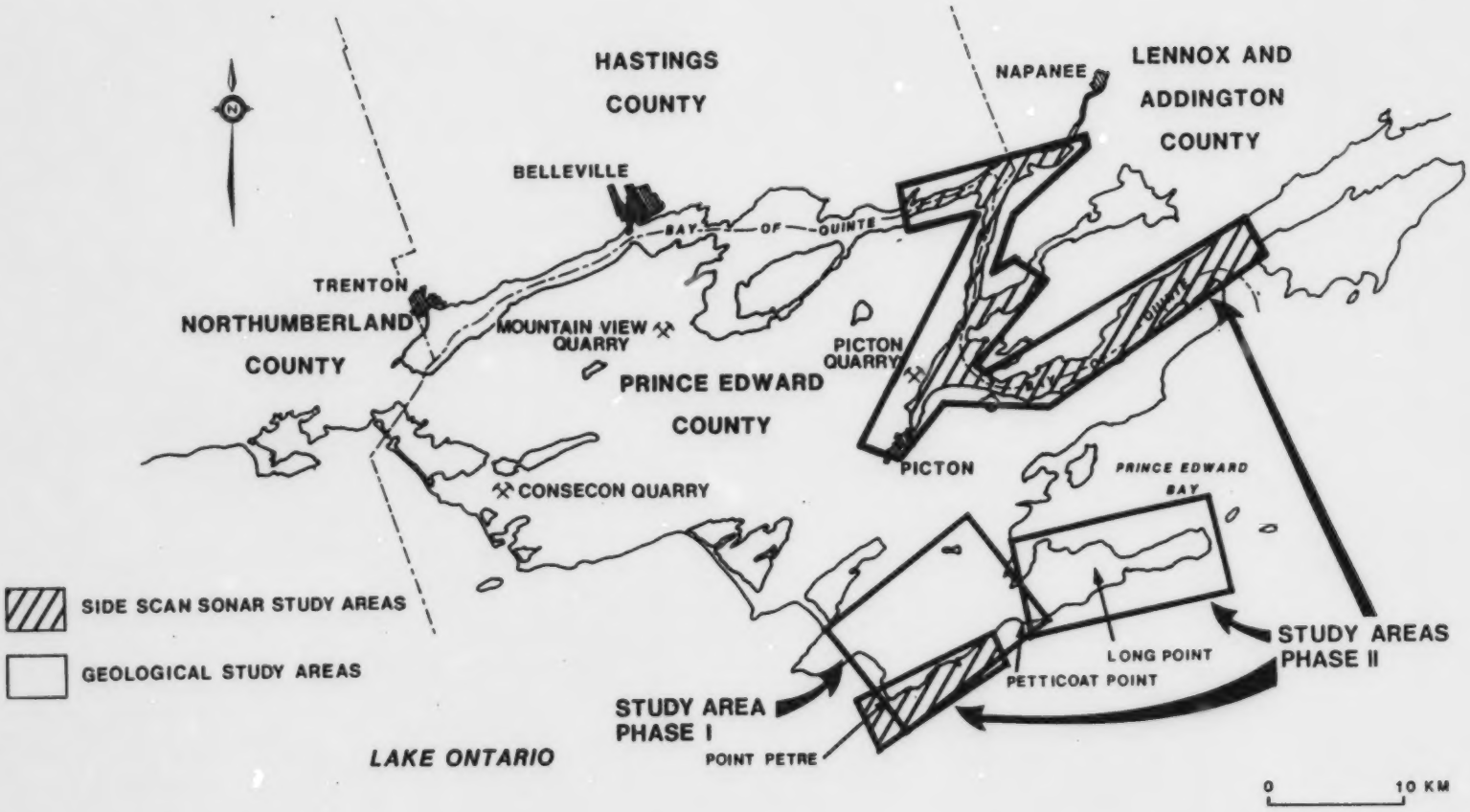

Figure 3: Location of study areas, Prince Edward County.

The field mapping area, located in that area of South Marysburgh Township known as Long Point (Figures 2 and 3), encompasses approximately 50 square kilometres bounded by the Lake Ontario shoreline and Latitude 43°57′ N, Longitude 76°51′ W and Longitude 77°03′ W. Field mapping also included the documentation of structures in the Picton and Mountain View Quarries (44°07′ N Latitude, 77°03′ W Longitude; 44°21′ N Latitude, 77°04′ W Longitude) (Figures 2 and 3).

The side scan sonar and magnetic surveys were conducted in two offshore areas (Figure 3). The first area is located in Lake Ontario, southeast of the Phase I study area, and encompasses approximately 10 square kilometres bounded by the Lake Ontario shoreline on the northwest, Latitude 43°49′ N to the south, and Longitude 77°05′ W and Longitude 77°11′ W. The second area is located northeast of the county, along the three arms of the Bay of Quinte and consists of over 85 line kilometres of survey.

1.3 PREVIOUS WORK IN STUDY AREA

The bedrock geology of Prince Edward County was mapped on a reconnaissance scale by Kay (1937, 1942), Liberty (1961), Carson (1980, 1981b, 1982) and again by Williams (1984). The Quaternary geology was mapped by Leyland (1982, 1983, 1984). The mapping, due to its reconnaissance nature, did not reveal many of the features

and structures present in the Quaternary deposits and in the bedrock of the study area.

The best exposures of the Paleozoic bedrock occur along the shoreline of Lake Ontario. A stereographic examination of aerial photographs of the shoreline regions of Prince Edward County was conducted by Creasy (1976) who identified a number of folds, domes and faults.

In 1987, mapping of the study area was undertaken to examine and identify features of both the Quaternary deposits and the Paleozoic strata observed on 1:10,000 and 1:2000 scale false-colour infrared aerial photographs of the Phase I mapping area, as well as previously mapped or identified structures (Liberty 1961; Creasy 1976). The Quaternary deposits were examined by Gorrell (1988), and the Paleozoic bedrock structures were examined by McFall (McFall and Allam 1990). The results of these preliminary investigations indicated the need for additional, more detailed work on a number of the structures in order to assess their characteristics and possible origin.

The topography in the Phase I study area is generally flat to very gently undulating and the relatively continuous bedrock exposure along the shoreline of Lake Ontario consists of predominantly flat-lying to gently dipping bedding plane surfaces with little or no exposure of the strata in cross-section. Cross-sectional exposures of the bedrock are limited to a few road cuts and localized cliff exposures in the western part of the study area. Observations of the bedrock geology have

therefore largely been restricted to the plan view which has led to uncertainties regarding the third dimension of some bedrock structures. To gain a better understanding of these structures at depth, investigations in 1989 focussed on cross-sections of the strata exposed in the Picton and Mountain View quarries and in the shoreline cliffs along the south side of Prince Edward Bay at the southeastern tip of the peninsula (Figure 2 and 3).

1.4 BEDROCK GEOLOGY

The study area is underlain by rocks of Ordovician age that rest unconformably upon the Precambrian basement (Figure 4) and are overlain by a thin veneer of Quaternary and Recent deposits. At the southeast tip of Long Point the total thickness of the Paleozoic succession is 262.7 metres as determined by the Hirchey No. 1 borehole (Department of Energy and Resources Management 1965). This borehole provides the only data on the thickness of the Paleozoic strata in the southeastern part of the county. On a regional scale, these strata dip very gently at 1 to 3 degrees toward the south, therefore the thickness of the Paleozoic succession elsewhere in Prince Edward County is generally less as a result if it's up dip location.

The Lindsay Formation forms much of the bedrock surface (Figure 5) and consists of thin to thick beds of limestone with

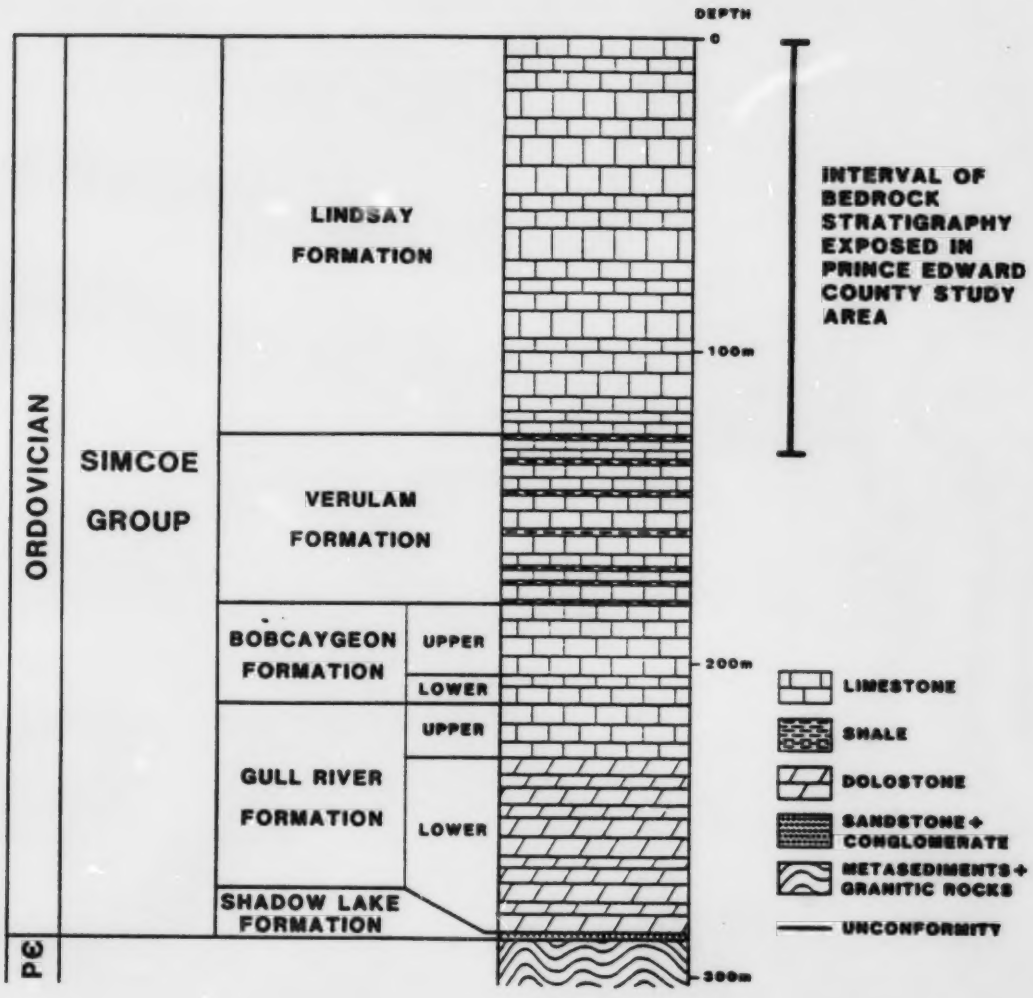

Figure 4: Generalized stratigraphy, Prince Edward County (geology adapted from Williams and Trotter 1984)

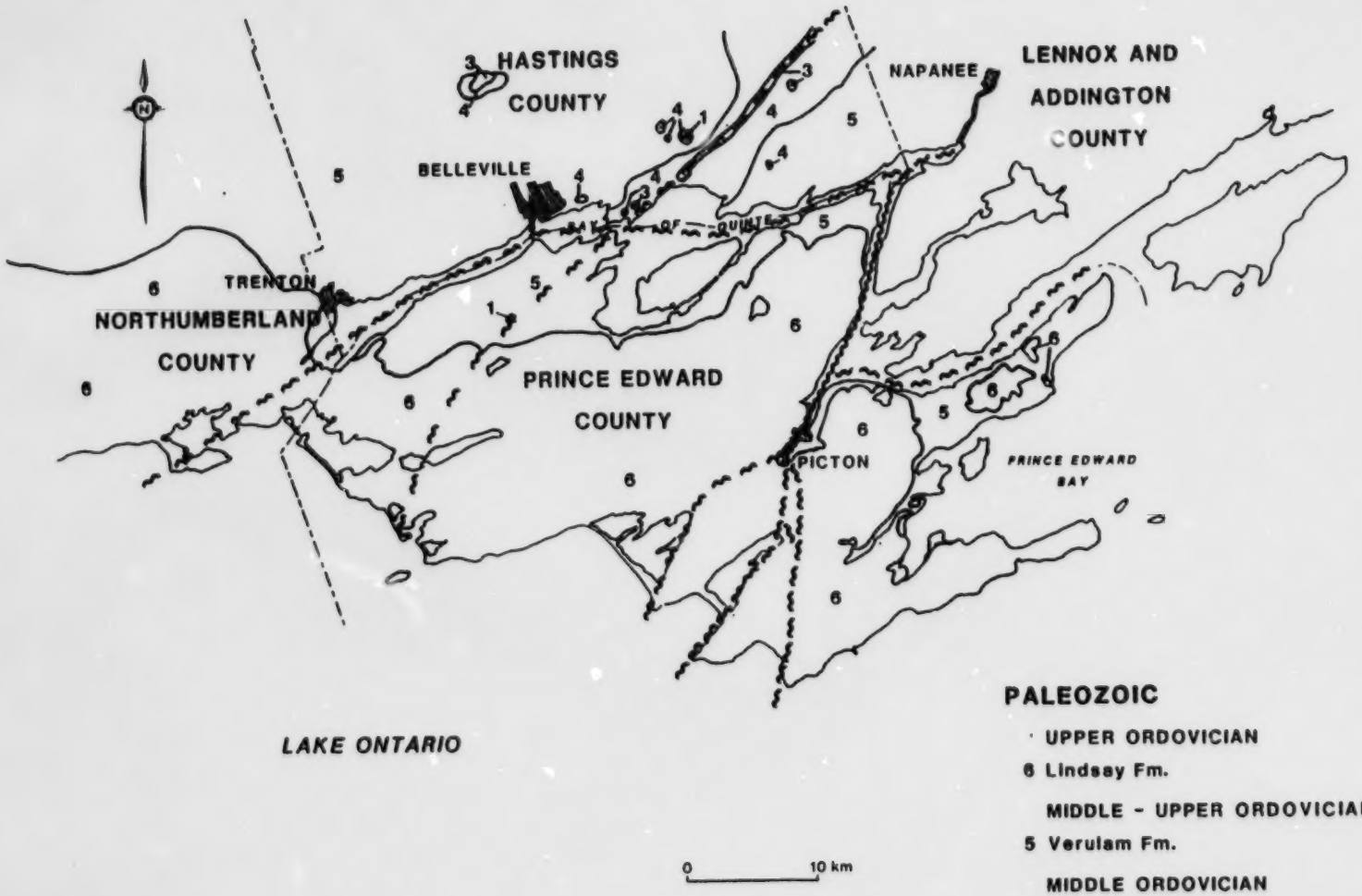

Figure 5: General bedrock geology map, Prince Edward County.

irregular shaly partings which impart a nodular texture. The Verulam Formation, which underlies the Lindsay Formation, consists of interbedded limestone and shale and exposure is limited primarily to the lower 1 to 2 metres of strata in the cliff exposures of Long Point and in the lowest lift and floor of the Picton Quarry.

The Phase I study area is cut by the eastern arm of the Picton Fault which extends from Point Petre north-northeastward, through Picton, and along one arm of the Bay of Quinte, known as Long Reach (Figure 2), which is part of the Bay of Quinte study area. The Picton Quarry is located adjacent to the fault to the west side of Long Reach. On a local scale, deformations of the bedrock have been observed in the form of domes, pop-ups and faults that may be related to high horizontal stresses within the region (White et al. 1974).

1.5 ACKNOWLEDGEMENTS

This project was funded by the Ontario Geological Survey, Ministry of Northern Development and Mines with additional funding provided by the Atomic Energy Control Board. Additional support was provided by the Ontario Centre for Remote Sensing, Ministry of Natural Resources through the supply of aerial photographs for the project. Resource assistance for this work was supplied by Ontario Hydro and the Great Lakes Division,

Ontario Ministry of the Environment. Although the side-scan sonar data were collected under a contractual agreement by McQuest Marine Sciences Limited, through an interest in the project they donated the magnetometer data to the Survey. Information and support by members of the Multi-Agency Group for Neotectonics in Eastern Canada is greatly appreciated.

The authors would like to thank Lake Ontario Cement (Picton Quarry) and McFarland Construction Company (Mountain View Quarry) for allowing access to their properties and to acknowledge the consideration of David Demille and Scott Babin (Lake Ontario Cement Co.) while visiting the Picton Quarry.

2.0 REGIONAL FRAMEWORK

2.1 STRUCTURAL SETTING

Part of the regional framework of the Prince Edward County and eastern Lake Ontario region can be defined by major structures that are predominantly oriented northeast-southwest (Figure 6). These include the Salmon River Fault[1], the Picton Fault System (Liberty 1960), the Napanee Fault (Liberty 1961), Robertson Lake Mylonite Zone, and the Frontenac-Sharbot Lake Terrane Boundary (Easton 1988). The Clarendon-Linden Fault System in western New York State has been documented as passing northeastward into Lake Ontario, trending towards Prince Edward County (Fakundiny et al. 1978) along the Scotch Bonnet Rise (Hutchinson et al. 1979). The Picton Fault is known to extend north-northeastward to connect with the Napanee Fault.

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[1] The Salmon River Fault was described by Liberty (1963, p. 12) in a manner which gives the impression that he actually saw the fault. However, his map indicates it to be an assumed fault. The Ontario Geological Survey will undertake a drilling programme in the Autumn of 1990 to attempt to clarify the status of this structure. Until that work is completed, the structure is to be considered as an assumed fault (Figures 6 and 8).

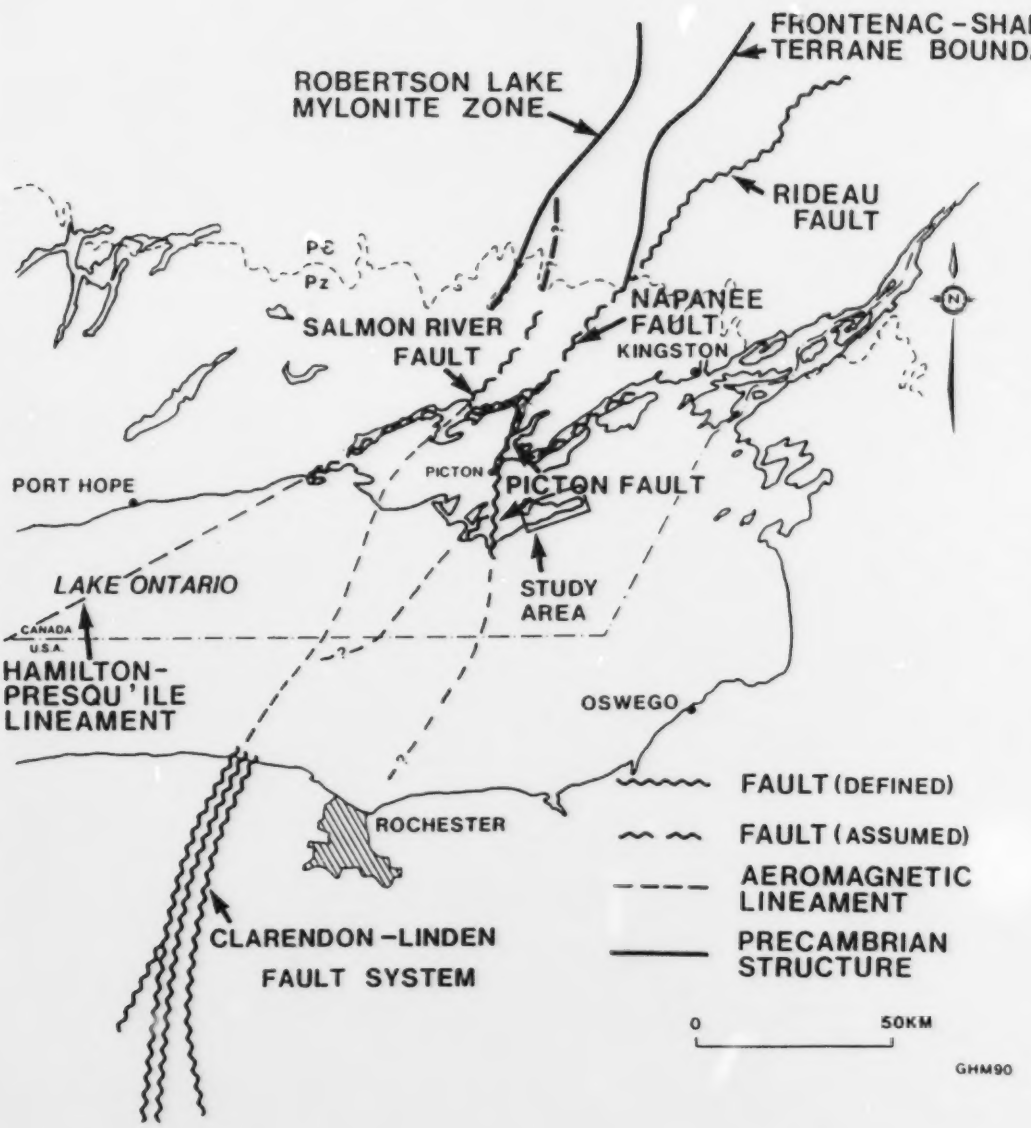

Figure 6: Regional setting of the eastern Lake Ontario area illustrating some of the major structural features discussed in the text (Precambrian geology adapted from Ontario Geological Survey (in Press); Paleozoic geology from McFall and Allam (1990)).

Collaboration between Precambrian and Paleozoic geologists at the Ontario Geological Survey in the preparation of a revised bedrock geology map has resulted in a better understanding of the relationship of known faults in the Precambrian and Paleozoic terranes. The Picton-Napanee Fault extends north-northeastward to connect with the Rideau Fault and the Frontenac-Sharbot Lake Terrane Boundary (Ontario Geological Survey, in press). The contact between the Frontenac and Sharbot Lake terranes near Maberly is sharp, probably represents a thrust fault, and locally the boundary zone is cut by syn- to post-tectonic granitic intrusions (Easton 1988). The Rideau Fault is marked by an almost one kilometre wide zone of brittle mylonites that cut, and therefore post date, the rocks of the Frontenac Terrane (R. M. Easton personnal communication 1990).

A total-field aeromagnetic map of eastern Lake Ontario (Geological Survey of Canada 1987) (Figure 7) reflects changes in the magnetic characteristics of the Precambrian basement rocks. Prominent geophysical lineaments identified on this map coincide with bathymetric anomalies along a northeasterly trending line which connects the Clarendon-Linden Fault with the assumed Salmon River Fault and to the western arm of the Picton Fault System (Figure 6). A second, parallel geophysical lineament begins near Rochester New York, crosses Lake Ontario in a northeasterly direction, and connects with the eastern arm of the Picton Fault

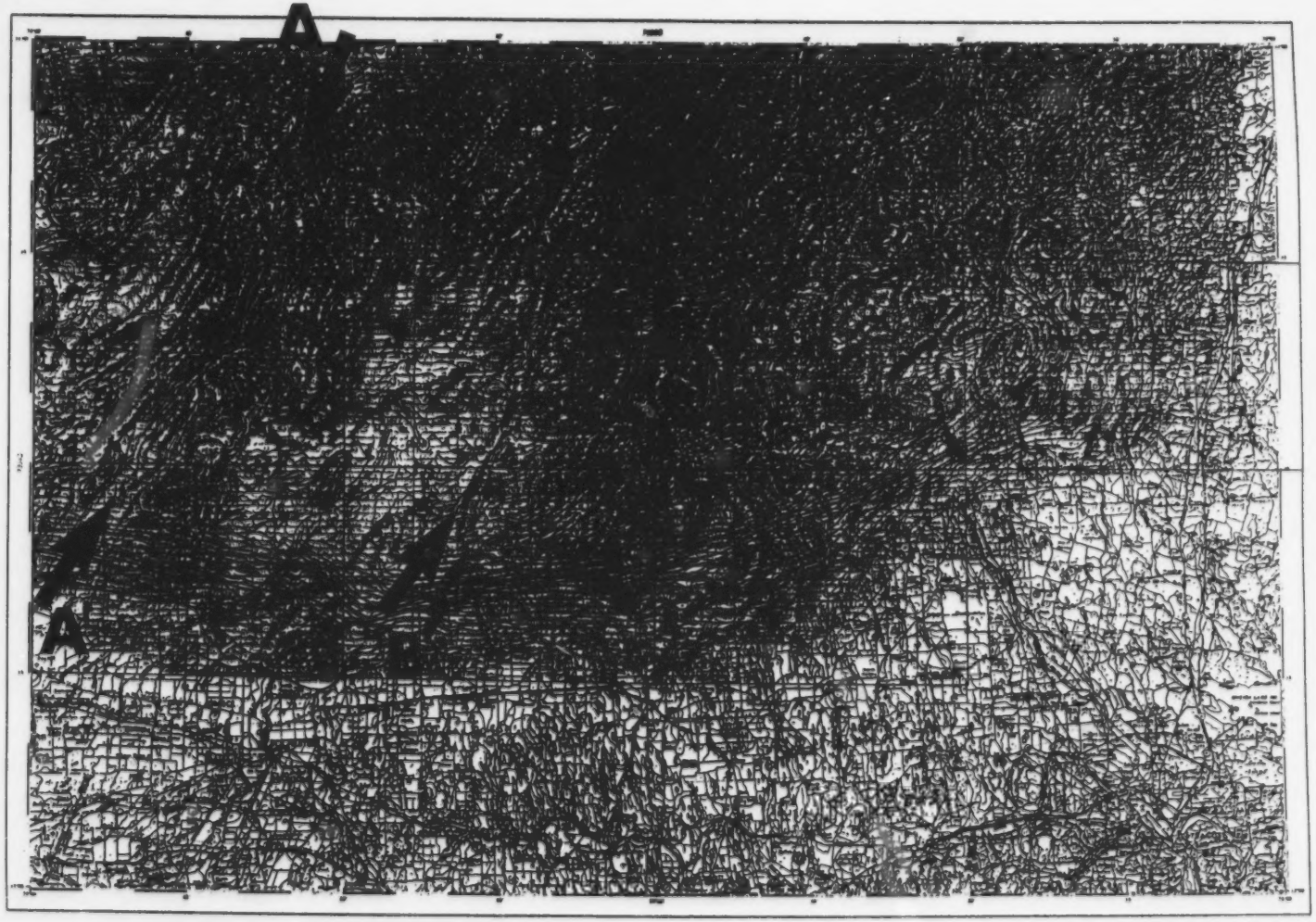

Figure 7: Total Field Aeromagnetic map of eastern Lake Ontario (Geological Survey of Canada Map 7333G). Arrows A-A' denote aeromagnetic lineament that is collinear with Scotch Bonnet Rise and links the Clarendon-Linden Fault System with the assumed Salmon River Fault. Arrows B-B' denote the Rochester to Point Petre (Picton Fault) aeromagnetic lineament.

which crosses the western part of the study area. This second lineament was also identified by Hutchinson et al. (1988).

The Clarendon-Linden and Picton Fault Systems have been mapped at surface, have bathymetric expressions and coincide with magnetic lineaments in the basement. This indicates that they cut through both the Paleozoic and Precambrian rocks and are continuous from western New York State to north of Prince Edward County, possibly as far as the Ottawa-Bonnechere Graben. The distinctive differences in magnetic signatures across the faults implies involvement of the Precambrian basement. This is supported by the apparent connection of the faults in the Paleozoic with terrane boundaries and known faults in the Precambrian rocks (Ontario Geological Survey, in press).

2.2 SEISMICITY

Two low magnitude earthquakes were reported within Prince Edward County during 1987-88 (Figure 8). The first earthquake was not recorded by the Geological Survey of Canada and was felt only in the Salmon Point area. It occurred during the winter (1987), approximately around Christmas time. The second earthquake was recorded by the Geological Survey of Canada (Geological Survey of Canada 1988). It occurred at 6:22 AM (local time) on September 9, 1988. The epicentre was located at

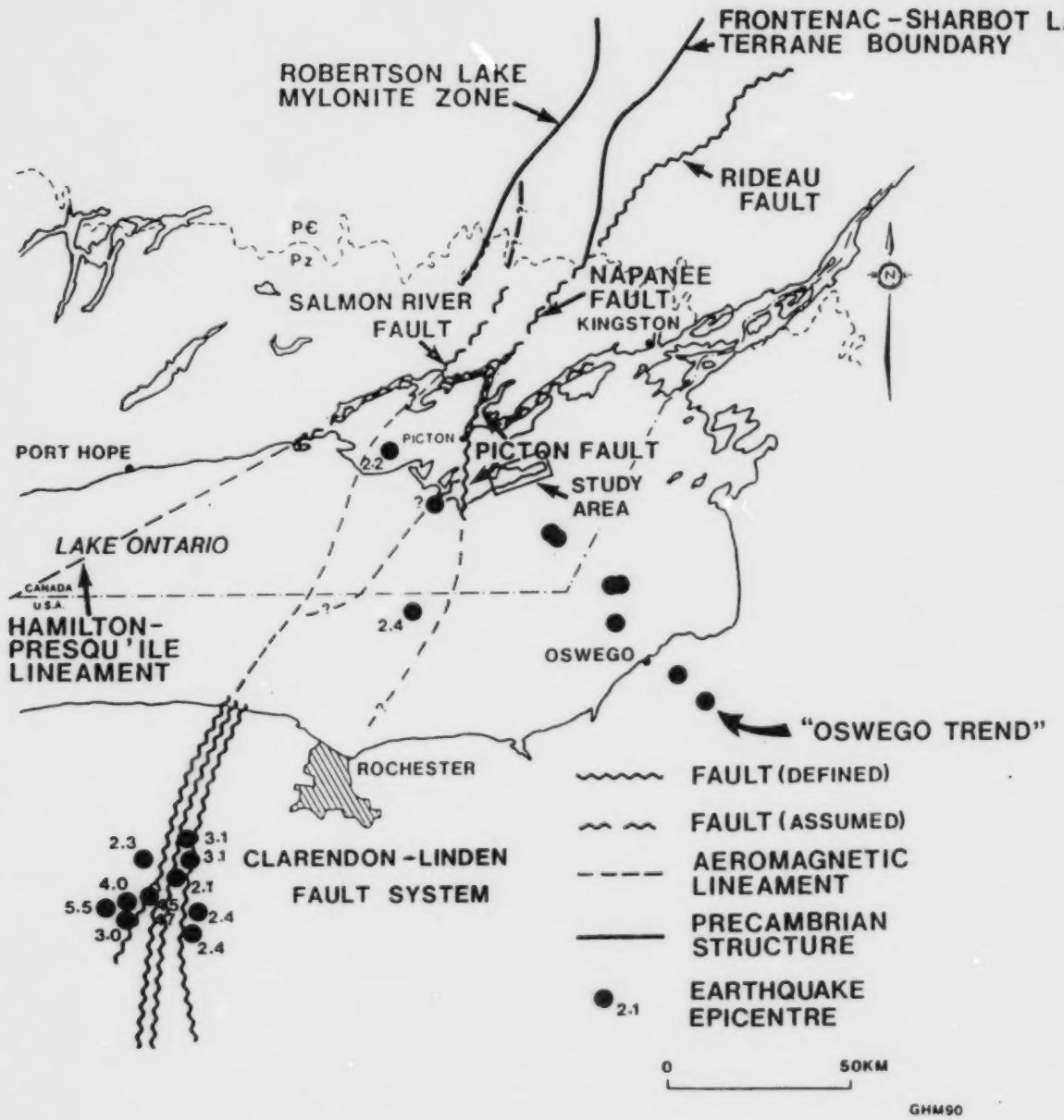

Figure 8: Regional setting of the eastern Lake Ontario area illustrating major structural features discussed in the text and seismicity (numbered earthquake data courtesy of the Geological Survey of Canada (1989), unnumbered data from Lamont-Doherty Observatory. Geology adapted from Ontario Geological Survey (in press) and McFall and Allam (1990)).

43.989 °N Latitude and 77.403 °W Longitude (the Consecon area) and had a magnitude of 2.2 at 10.3 kilometres depth.

An earlier earthquake was reported south of Prince Edward County in Lake Ontario. This earthquake was originally catalogued as occurring on March 13, 1979 at 43.56 °N Latitude 76.60 °W Longitude with a magnitude of 1.9 and an estimated depth of 18 kilometres (Earth Physics Branch 1979). This event was subsequently re-evaluated and relocated by the Geological Survey of Canada Seismology Division to 43.59 °N Latitude and 77.330 °W Longitude with a magnitude of 2.4 at 18 kilometres depth.

2.3 DISCUSSION

All three earthquakes appear to be related to the regional faults of eastern Lake Ontario (Figure 8). The 1979 earthquake epicentre was described in the Provisional Catalogue of the Seismological Service of Canada (Earth Physics Branch 1979) as having been located on a northwest trending line of earthquake epicentres extending from Oswego, New York, to Prince Edward County. It has now been relocated by seismologists from the Geological Survey of Canada (Geological Survey of Canada 1988) so that it is near the eastern arm of the Picton Fault. The 1987/88, unrecorded earthquake occurred near Salmon Point which is the western arm of the Picton Fault. The 1988 2.2 magnitude earthquake occurred in the vicinity of the Consecon Quarry which

is situated near the extension of the assumed fault along the valley of the Salmon River. On May 1, 1988, a 2.1 magnitude earthquake located on the Clarendon-Linden Fault (42.947 °N Latitude and 78.115 °W Longitude) (Geological Survey of Canada 1988) in western New York State was recorded by the Canada Seismic Network. Numerous other earthquakes, some in excess of magnitude 5.0, have also been reported on or close to the Clarendon-Linden Fault System. This suggests that the regional fault system (Clarendon-Linden/assumed Salmon River/Picton/Napanee/Rideau Fault System and Frontenac-Sharbot Lake Terrane Boundary) (Figure 6) may be seismically active both in New York State and in Ontario.

3.0 DETAILED FIELD MAPPING

3.1 INTRODUCTION

During the 1989 field season, a variety of activities was conducted during field mapping. Much of the work was directed towards further examination and delineation of bedrock structural features such as faults, open fractures and possible fold structures.

The best exposures of the Paleozoic bedrock occur along the Lake Ontario shoreline. Detailed observations of the bedding attitudes and fractures along the shore line were made during the 1987 and 1988 field seasons. Man-made exposures, such as abandoned pits or quarries, excavated cattle ponds, road-cuts and bulldozer-cleared bedrock outcrops were also examined in detail.

In Phase I, detailed investigations of probable neotectonic features were confined to an area of approximately 100 square kilometres in the southern part of Prince Edward County, (Figure 3). The topography is generally flat to very gently undulating and the relatively continuous bedrock exposure along the shoreline of Lake Ontario consists of predominantly flat-lying to gently dipping bedding plane surfaces with little or no exposure

of the strata in cross-section. Bedrock exposures in cross-section are limited to a few road cuts and localized cliffs in the western part of the study area. Observations of the bedrock geology have, therefore, largely been restricted to the plan view which has led to uncertainties regarding the third dimension of some bedrock structures. To gain a better understanding of these structures at depth, Phase II field investigations were conducted outside of the initial study area and have focused on the south side of Prince Edward Bay at the southeastern tip of the peninsula. There, the Middle Ordovician Lindsay and Verulam Formations are exposed in cross-section in shoreline cliffs of up to 15 metres high.

The preliminary interpretation of aerial photographs of the Long Point study area indicates the presence of a number of lineaments which are identified on Figure 9 by dashed lines; the heavy dashed lines are prominent lineaments and lighter dashed lines are less obvious ones. The lineaments form a rectilinear pattern oriented north-northeast to south-southwest and approximately east-west. At surface, most of these are marked by lines of trees and bushes, some are linear depressions.

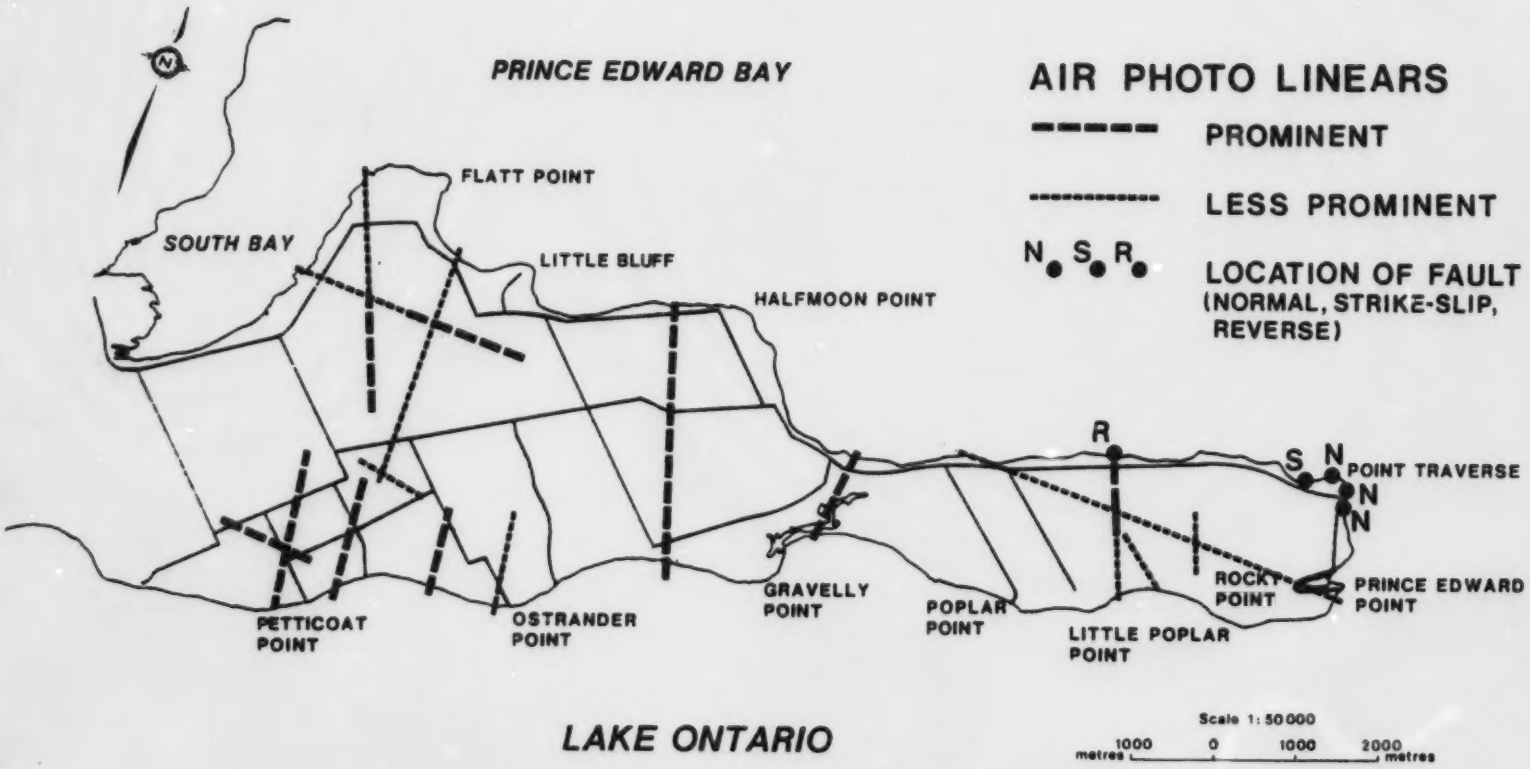

Figure 9: Index map and aerial photolineaments of Long Point study area, Prince Edward County.

3.2 JOINTS

In the Phase I study area, joints are readily observable along the shoreline and in road-cuts and excavations. These are not always "tight" with sides touching, but range in width from a few millimetres to over 30 centimetres (Gorrell 1988; McFall and Allam 1990). Sporadic calcite infillings were observed, and weathered edges were most often observed at exposures along the lake front. In vertical outcrop, the joints were commonly observed to be vertical to sub-vertical, although this is not the case in the Point Petre area (Figure 2) where dips of up to 78 degrees were observed. Multiplex joints (Fakundiny 1978), which are narrow zones of multiple fractures, were observed in one location. The dominant joint orientations determined for the Phase I study area are 060° and 125° (Gorrell 1988; McFall and Allam 1990).

Preliminary results of the joint data gathered at bedrock exposures along the shoreline within the Long Point study area are presented in Figure 10. The dominant joint directions are 301°/89°[1], and 257°/88°[1], although 278°/90°[1], and 216°/90°[1], were also observed (Figure 10, Appendix A).

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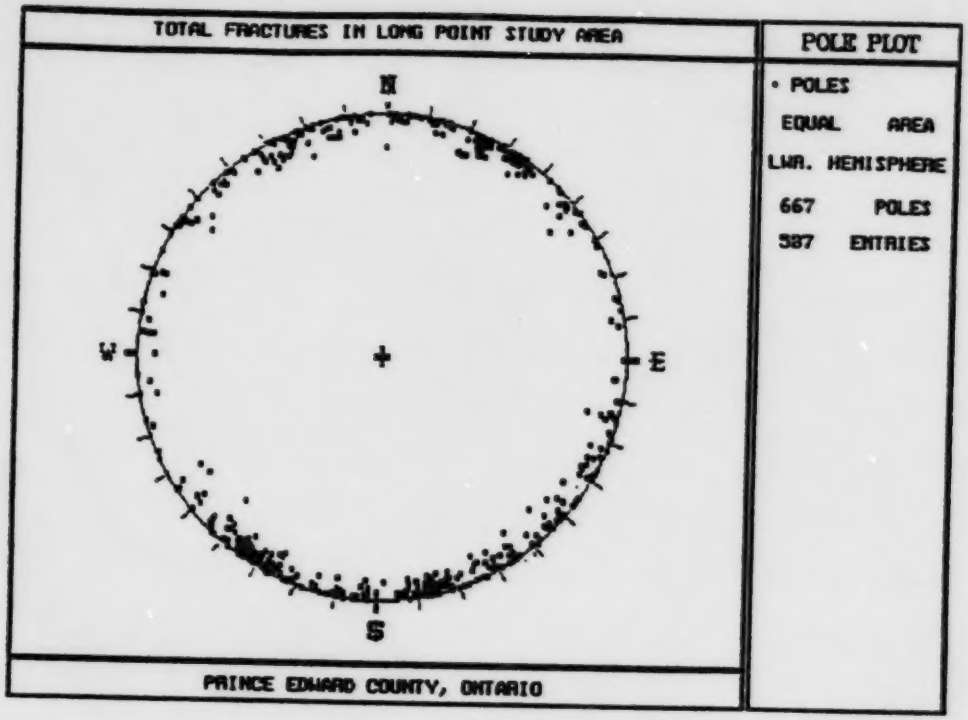
[1] Right hand rule.



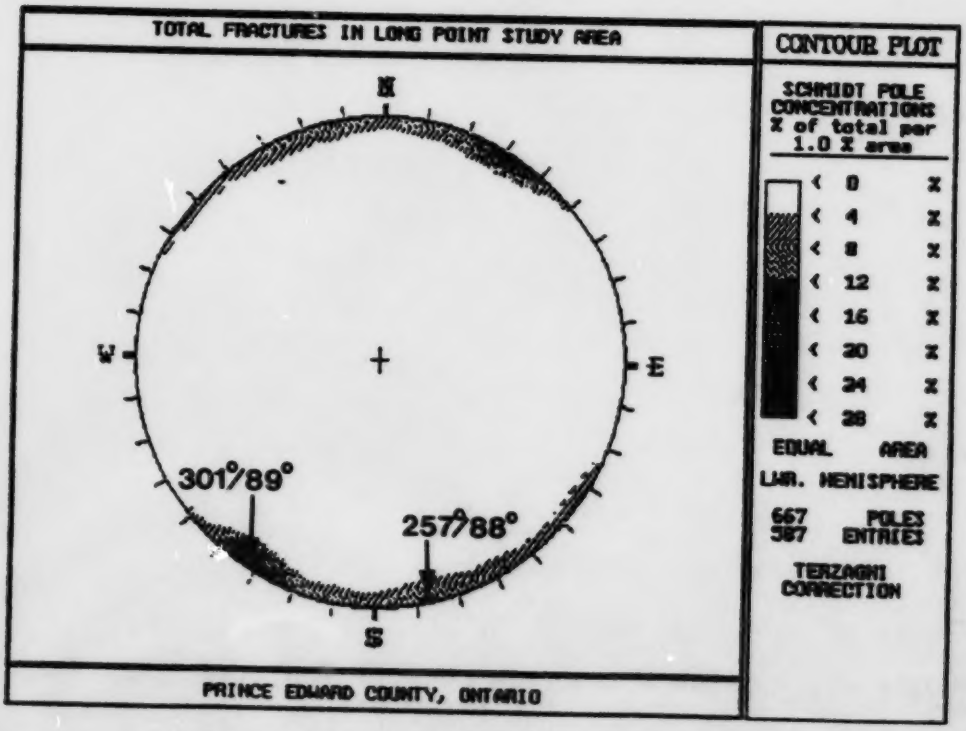


Figure 10: Fracture orientations, Long Point study area.

3.3 OPEN FRACTURES

During the 1987 and 1988 field investigations, open fractures were observed to occur throughout the Phase I study area. A preferred orientation for the open fractures is not immediately apparent but they do reflect the main joint orientations (060° and 125°) of the Phase I study area (Gorrell 1988; McFall and Allam 1990).

Open fractures are not common in the Long Point shoreline cliffs which expose the strata in cross-section. Those fractures that are open at the ground surface, at the top of the 10 to 15 metre cliffs, are generally closed at the base of the cliff. The few openings that can be observed at the base of the cliff exposures are either a) joints that are open 1 to 5 millimetres, infilled with clay material (possibly soil from above) and with no apparent evidence of vertical offset of the strata or slickensided joint surfaces, or b) are recognisable faults (discussed under Faults).

It is difficult to determine how and when the joints were opened. In some locations in the Phase I study area, the openings are interpreted as having occurred prior to glaciation as large Precambrian boulders were observed wedged into the openings, probably by overriding ice (Gorrell 1988). Some open fractures may have been widened by dissolution of the limestone walls. These are most common in areas exhibiting other

dissolution features such as rounding and incising of the limestone surfaces and sink holes. Still other open fractures exhibit relatively fresh surfaces with little or no apparent evidence of dissolution and some, like those at an abandoned beach (Gorrell 1988), appear to have opened or to have been rejuvenated more recently.

3.4 FAULTS

Faults can be observed in the cliff exposures along the north side of Long Point (Figure 11). Most of the exposures are only accessible by boat. The orientations, dips, and sense of movement have been documented and are listed in Table 1 and illustrated in Figure 11.

3.4.1 Normal Faults

A normal fault that is well exposed on the beach at Point Traverse trends 120°/80°[1] (Table 1 and Figure 11). The fault plane is deflected as it passes through the variations in composition of the strata, resulting in a curvilinear fault trace exposed in the outcrop (Figure 12). The fault zone is weathered

[1] Right hand rule.

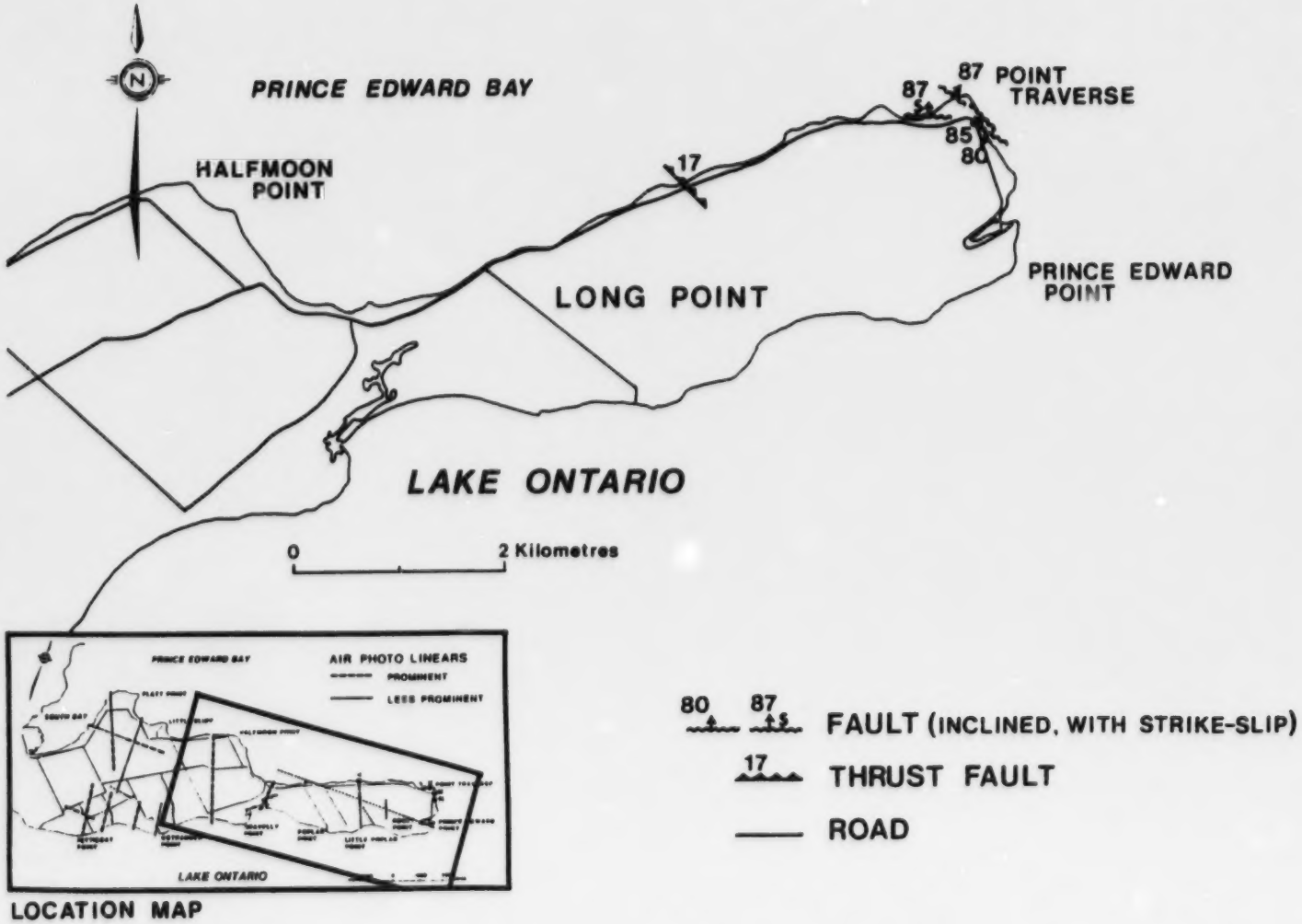


Figure 11: Location of faults, Long Point study area.

TABLE 1

TABLE OF FAULT DATA

LOCATION	UTM	STRIKE	DIP	VERTICAL DISPLACEMENT	SLICKENSIDES (PITCH)	INFILLING
NORMAL FAULTS						
POINT TRAVERSE BEACH	350450E 4867250N	120	80 SW	40 CM	VERTICAL	NOT APPARENT
EAST SIDE POINT TRAVERSE	354000E 4867450N	135	85 SW	70 CM	NOT SEEN	NOT APPARENT
NORTH SIDE POINT TRAVERSE	350000E 4867450N	305	87 NE	1.25 M	NOT SEEN	NOT APPARENT
REVERSE FAULTS						
NORTH SIDE OF LONG POINT	347600E 4866800N	315	17 NE	2.25 M	NEAR-VERTICAL (82/053)	CALCITE
NORTH SIDE OF LONG POINT	347600E 4866800N	144	19 SW	2 CM	NEAR-VERTICAL (86/058)	CALCITE
ZONE OF STRIKE SLIP FAULTS						
NORTH SIDE OF POINT TRAVERSE	349900E 4867400N	273	87 N	0 TO 5 CM (MAX)	SUB-HORIZONTAL	CALCITE

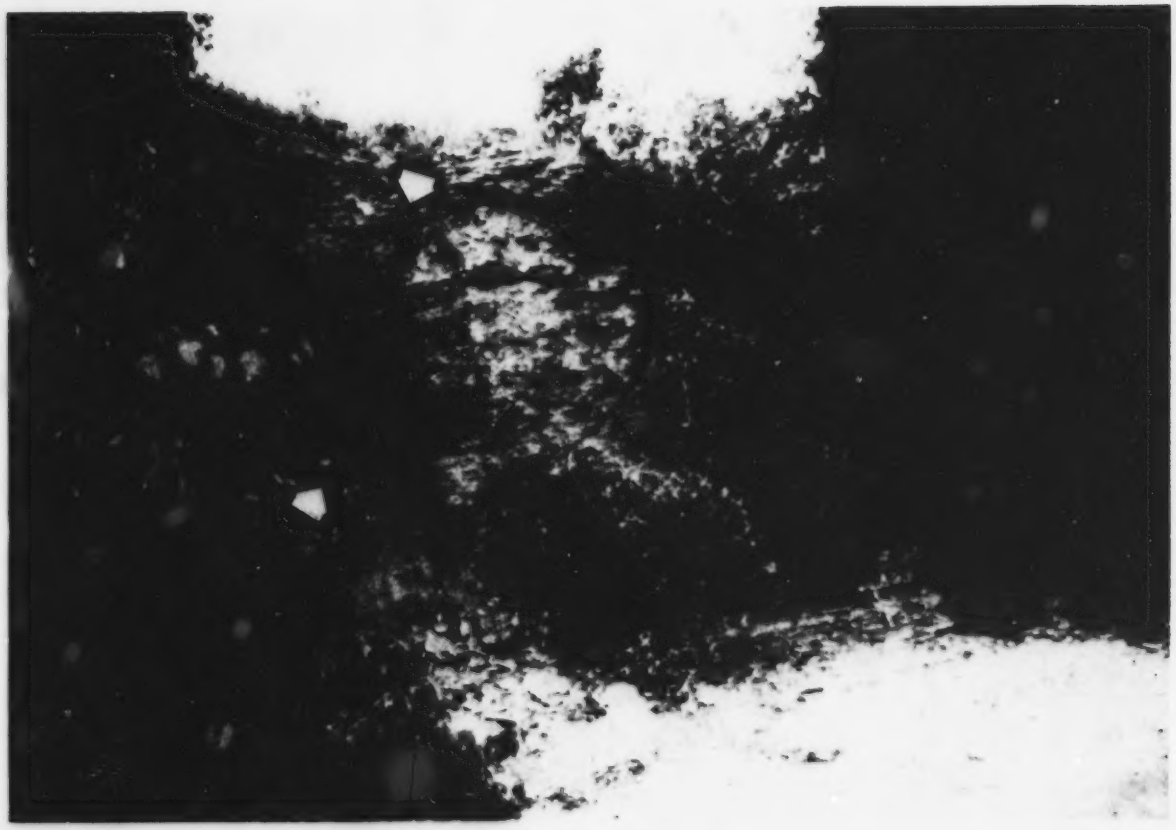


Figure 12: Normal fault exposed at Point Traverse beach, Long Point study area. Direction of fault movement is indicated by drag of the beds (A) adjacent to the fault (arrows).

with no apparent infilling material. Slickensides are not common, but when observed are vertical. Ductile drag of the adjacent strata has occurred on both sides of the fault plane for a distance of about 20 centimetres and the southwest side is down relative to the northeast.

About 230 metres northwest, along the eastern shore line of Point Traverse, is another normal fault (Figure 11). This fault trends 135°/85°[1]. Unlike the fault on the beach at Point Traverse, the fault plane is not curved and there is no deformation of the adjacent strata (Figure 13). Although slickensides were not observed on the surfaces of the fault, 70 centimetres of dip separation in a normal sense can be determined using prominent marker beds which can be identified on both sides of the fault. As with the first fault, the southwest side is down relative to the northeast.

A third normal fault, which trends 305°, is exposed on the north shore of Long Point (Figure 12). The vertical path of the fault plane is deflected as it passes through the variations in composition of the strata; the dip in the crystalline beds is 87° (Figure 14). Ductile drag along the fault is observed at the base of the exposure. The dip separation can be determined using a thin shale marker bed that is offset about 1.25 metres by the fault and the northeast side has moved down relative to the southwest. This relationship is the opposite to what was

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[1] Right hand rule.

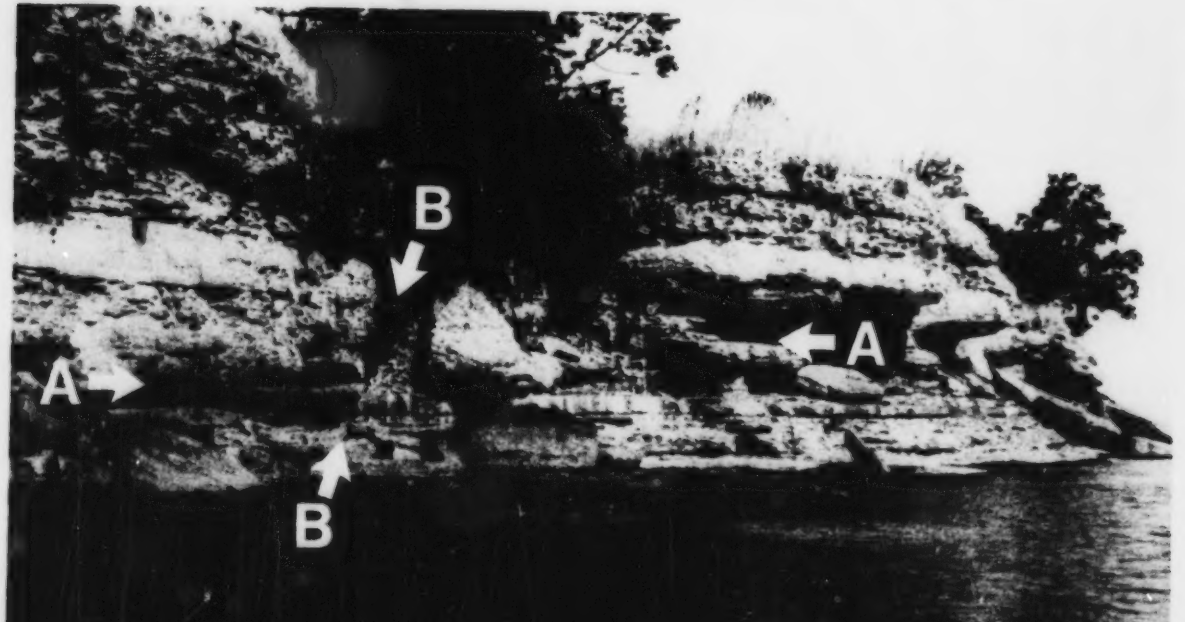
B
A
A
B

Figure 13: Normal fault exposed on the east side of Point Traverse, Long Point study area. Corresponding contacts (A) off set across the fault (B).

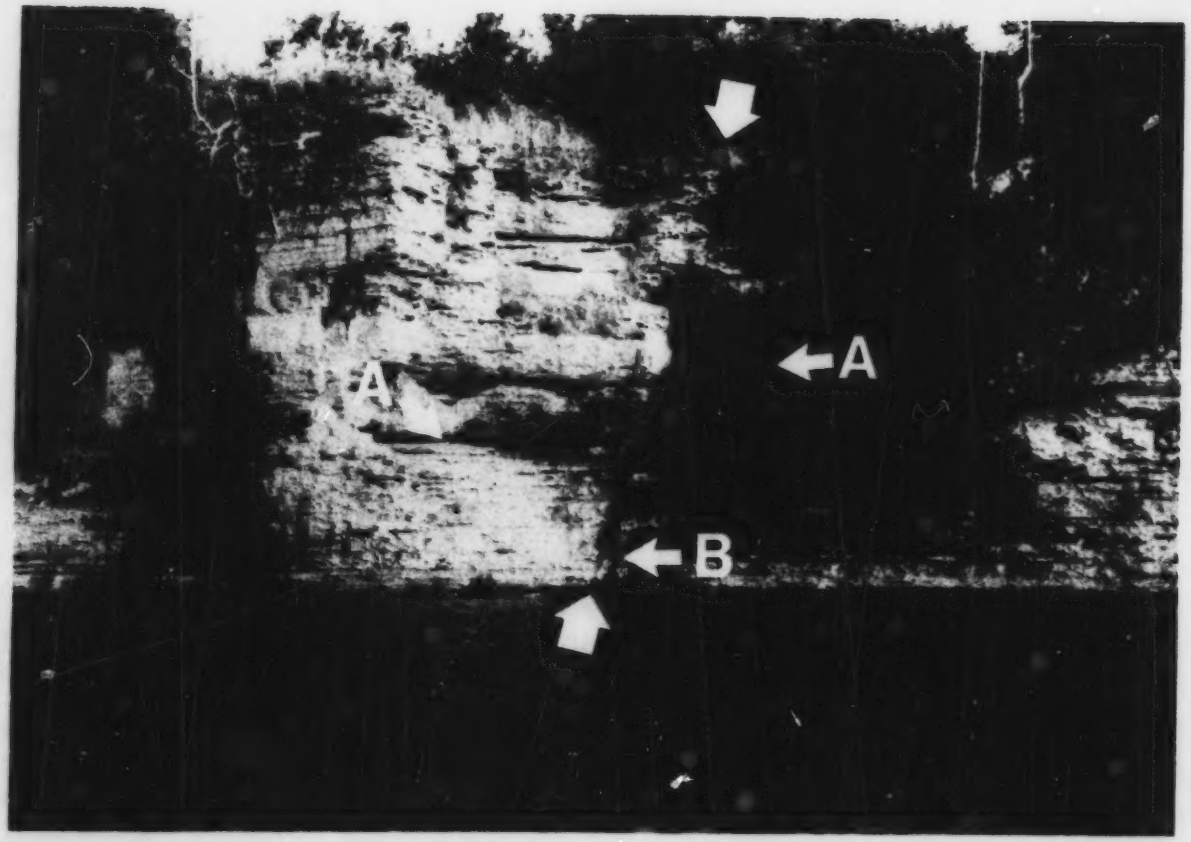

Figure 14: Normal fault exposed on north side of Point Traverse, Long Point study area. Thin shale layer (A) is offset by fault (arrow). Limestone beds near the waterline exhibit drag (B).

observed for the first two normal faults for which the southwest side is down relative to the northeast.

3.4.2 Reverse Faults

Gentle warping, probably due to ductile deformation, of the otherwise flat-lying beds over a distance of 30 to 40 metres can be observed in bedrock exposures on the north shoreline of Long Point, about 3 kilometres west of Point Traverse (Figure 11). In the middle of this gently deformed zone is a conjugate pair of low-angle faults striking 315° and 144° (Table 1). The main fault, which is oriented 315°, occurs where a prominent lineament observed on the aerial photographs intersects the cliff (Figure 9). Reverse movement of about 2.25 metres, or more, on the fault is possible, but the amount of movement is difficult to establish as potential marker beds in the exposure are poor (Figure 15). The surface of the footwall of the fault is exposed at the base of the cliff. Both the calcite infilling and limestone surfaces show steeply pitching slickensides (82°) indicating that the latest movement on the fault was predominently dip-slip, although there was also a minor strike-slip component.

The conjugate fault is observed about ten metres to the east. It has the same strike but dips in the opposite direction (Table 1).

Figure 15: Low angle reverse fault exposed on north shoreline of Long Point. Thin shale beds (A) are offset in a reverse sense across the fault and (B) are exposed at the base of the cliff.

3.4.3 Strike-slip Faults

Two closely spaced and intensely fractured zones occur on the north shore of Long Point about 400 metres west of Point Traverse (Figure 11). The fracture zones contain veins of euhedral calcite and cut an almost vertical expanse of what appears to be continuous, flat-lying strata. Strike-slip faults occur within the two fracture zones and generally trend 273° (Table 1). The faults are marked by calcite veins and the strike-slip motion is indicated by the presence of sub-horizontal slickensides on five of the fracture surfaces (Figure 16). There is very little vertical displacement; a maximum of 5 centimetres dip separation occurs on one of the faults. The faults are partially infilled with calcite which is generally euhedral. Complete infilling of the fractures is not common and the calcite has well-developed crystal terminations. This suggests that deposition of the calcite occurred after the strike-slip motion; perhaps during a later period of extension or tension. Where the vertical cliff face meets the water, the faults are marked by small caves that are elongated along the fault trace.

3.5 DISCUSSION

The exact mechanism for initial opening or rejuvenation of the open fractures is unknown, however it is possible that more

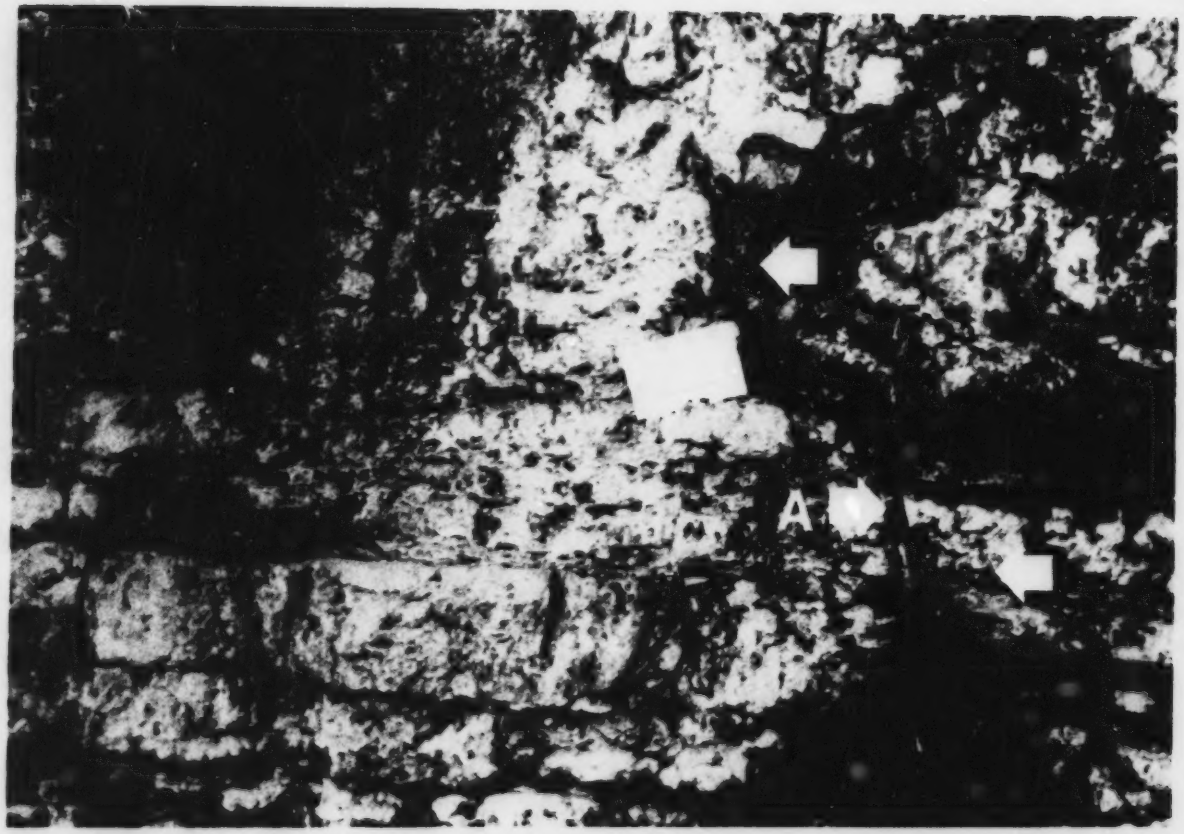

Figure 16: Strike slip fault (A) exposed in cross-section on north side of Point Traverse, Long Point. Arrows denote the surface of the fault where subhorizontal slickenlines were observed.

than one mechanism may have been responsible. Tension due to glacial unloading might possibly be responsible for openings preferring the northwest orientation, but their apparent concentration in one area and parallelism with the pop-ups (compressional features) brings this interpretation into question. Preferential weathering, or plucking by glacial ice sheets, of the highly fractured multiplex joints could also produce openings in the bedrock, as would dissolution of the limestone by large volumes of water at the base of the ice sheet, by glacial lakes which covered the region, or by post-glacial rivers and water courses.

Alternatively, if the multiplex joints observed in the Phase I study area are interpreted as small shear zones, then opening and/or rejuvenation of northwest trending joints may be the result of movement along faults which appear to be responsible for the "Oswego trend". The "Oswego trend" is a northwest trending alignment of seven earthquake epicentres (Figure 8) that extend from southeast of Oswego, New York, across Lake Ontario and intersects Prince Edward County approximately in the study area. Barosh (1986, Figure 15) identified generalized faults and fault zones that are spatially related to earthquakes. One of Barosh's probable fault zones extends northwest from Massachusetts to intersect Lake Ontario in the vicinity of Oswego. The "Oswego trend" therefore may be the northwest extension of this probable fault zone. Northwest to north-northwest trending faulting with probable Holocene movement has

been identified by Young and Putman (1990) near Oswego. Given the findings of Young and Putman (1990) and the inferences of Barosh (1986), then the distinct alignment of earthquake epicentres of the "Oswego trend" is quite possibly the result of rejuvenation of faults under Lake Ontario. It is also interesting to speculate on what influence movements of these faults may have in the Prince Edward County study area.

Previously it has been suggested (McFall et al. 1988) that not all of the open fractures observed in the study area were formed by dissolution alone and that some may have opened in response to changes in regional stress. The preservation of slickensided surfaces, which would have been removed by dissolution, and the presence of euhedral calcite, suggesting the precipitation and not dissolution, within the openings of the strike-slip faults indicate a different mechanism than dissolution. In the Phase I study area, at least two prominent northwest trending linear depressions, which appear to be open fractures, extend along strike from pop-up structures that appear to have formed along older faults (see Figure 17). This suggests that some of the open fractures may be related to reactivation and/or weathering of pre-existing faults. The observation of bedrock openings, which are related to faults, at ten metres below the surface in the Long Point area supports this interpretation.

Although it is probable that tectonic stresses are responsible for opening the fractures, equally convincing

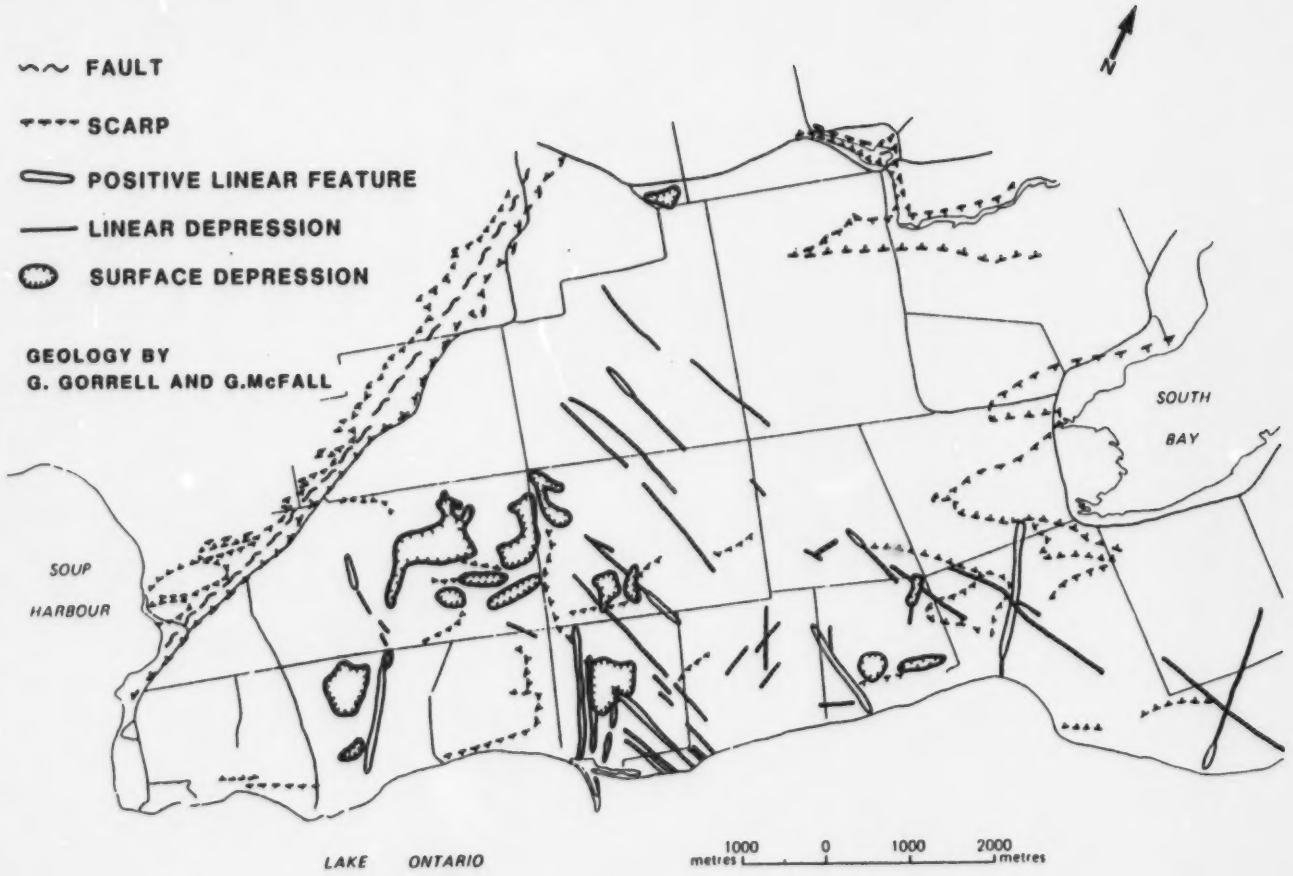

Figure 17: Distribution of bedrock features, Prince Edward County Phase I study area.

arguments can be made to support the other mechanisms mentioned above. It is also possible that several mechanisms have been operational in the evolution of the open fractures. However, there is presently no conclusive evidence to support any proposed mechanism and therefore additional work on this topic is indicated.

4.0 MOUNTAIN VIEW QUARRY

4.1 INTRODUCTION

The Mountain View Quarry is located on Highway 62 (UTM 311500mE 4883000mN), 17 kilometres northwest of the town of Picton (Figure 2). The quarry, owned and intermittently operated by the H.J. McFarland Construction Company (Derry et al. 1989), exposes a 10 metre vertical section of the Lindsay Formation. Here, the formation consists of thinly-bedded limestone with thin shale interbeds and partings. The uppermost metre of rock is weathered and rubbly. The quarry is situated on the top of, a 30 metre high bedrock escarpment which overlooks an extensive swamp to the north. The escarpment is oriented approximately east-west and is about 20 kilometres long. Williams and Trotter (1984) suggested the possible presence of a fault in area of the swamp and locate it from 1 to 2.5 kilometres to the north of the escarpment.

4.2 DESCRIPTION OF STRUCTURES

Fractures are widely spaced and generally not well developed so only thirty five fracture orientations could be recorded. The dominant fracture orientation are 068°/89°[1] and 282°/86°[1], with 155°/90°[1] and 177°/89°[1] also being common (Figure 18, Appendix A).

Brittle deformation is exhibited by a gentle concentric fold trending 335°, and a kink-band trending 169°/70°[1] (Figure 19). The fold is defined by fracture bounded, unbent segments that have been subjected to varying amounts of rigid body rotation. The kink-band is also composed of unbent, fracture bounded segments that form an asymmetrical inverted "v" structure. The structures are located on the north wall of the quarry and, as they are not observed on the far wall over 60 metres away, do not appear to have much lateral extent.

4.3 DISCUSSION

The dominant joint orientations are in keeping with those measured elsewhere within Prince Edward County (Figure 10). The axis of the concentric fold and the kink-band are oriented

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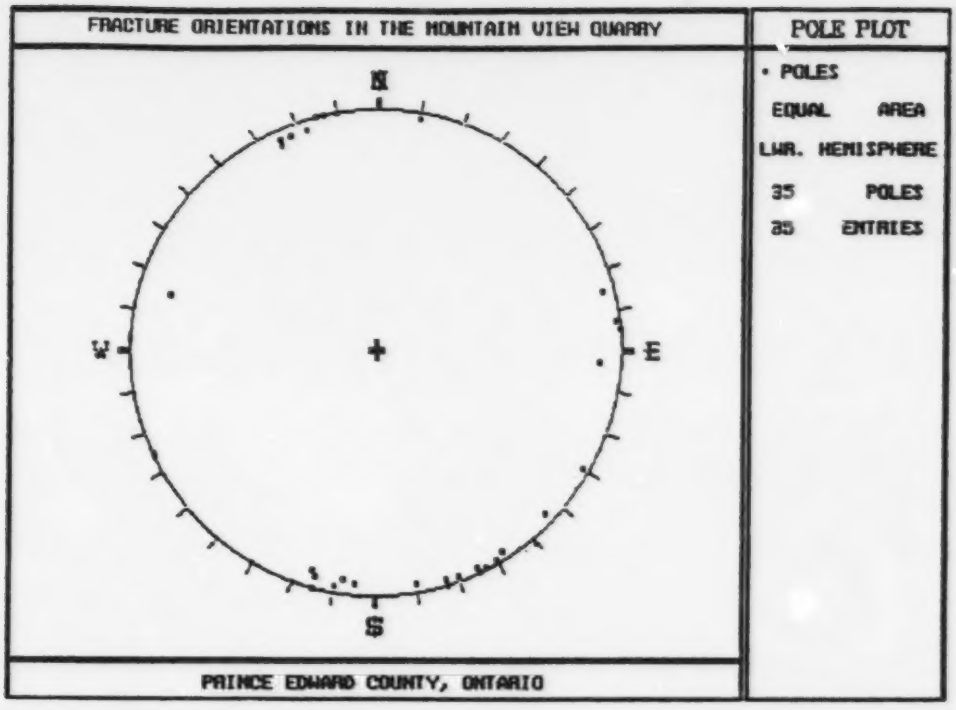
[1] Right hand rule.



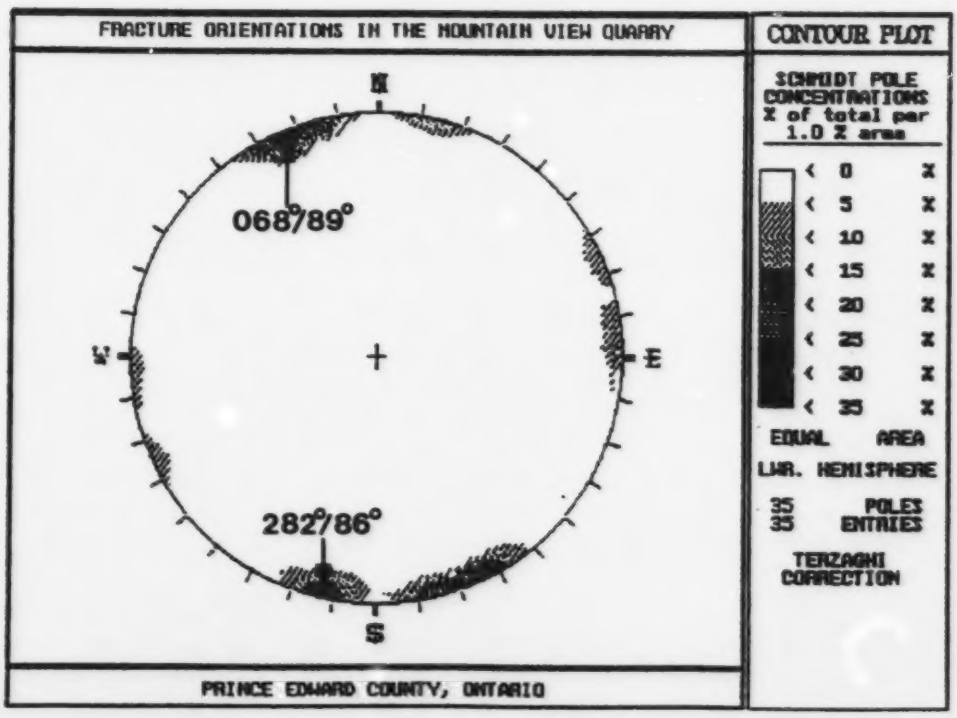


Figure 18: Fracture orientations, Mountain View Quarry, Prince Edward County.

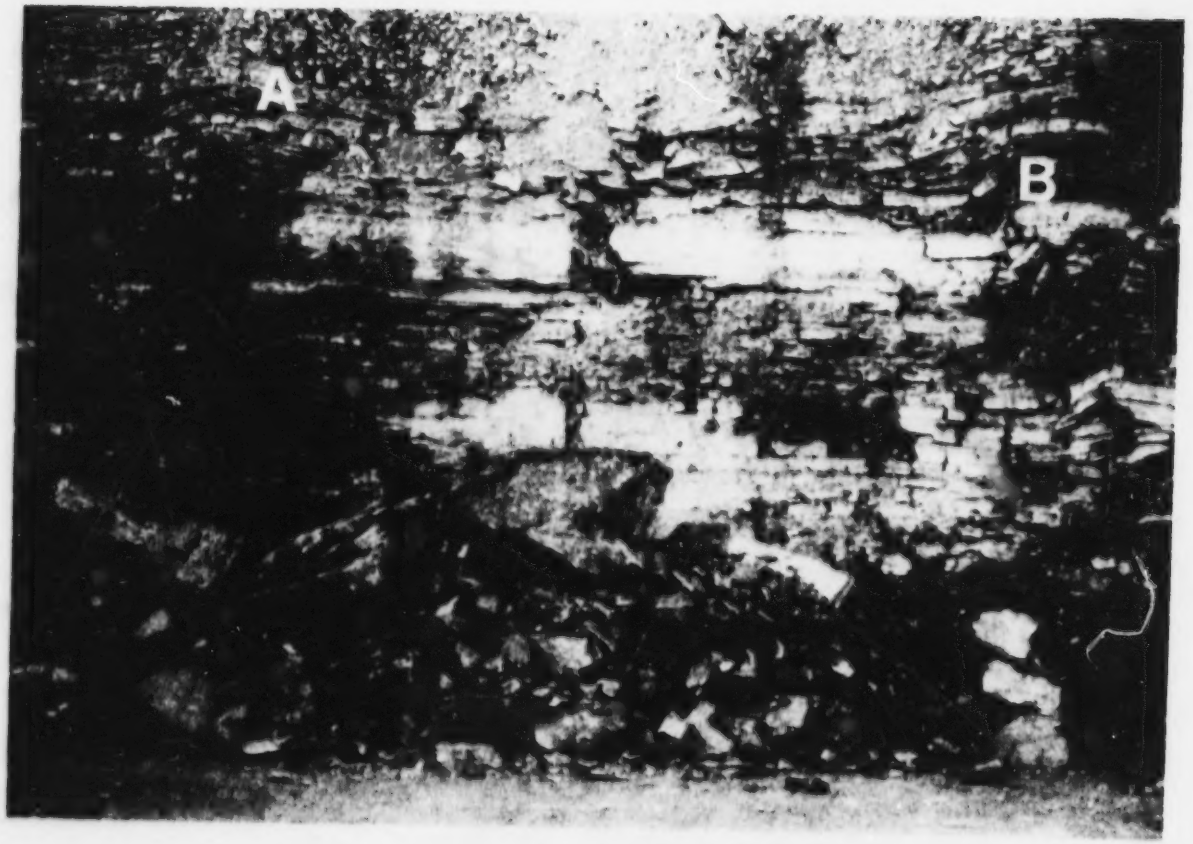


Figure 19: Brittle deformation features in the Mountain View Quarry, Prince Edward County. Structures present include a concentric fold (A) and a kink band (B). Scale by kink band is 1.8 metres long.

northwest-southeast and are perpendicular to the present day, principal horizontal compressive stress (Yang and Aggarwal 1981; Adams and Basham 1987). This could indicate that the structures are geologically recent, however, the time of formation of the structures is unknown other than the deformation occurred after pressure and temperature conditions ceased to support ductile deformation of the rock or that the strain rate was particularly rapid.

It is possible that the structures formed in response to either glacial flow to the southwest or tectonically derived stress. Glacial flow north of the quarry (Figure 2) was west-southwesterly as indicated by the orientations of drumlins in that area (Williams and Trotter 1984). On the other hand, Gorrell (1988) measured the ice flow direction in Prince Edward County Phase I study area and at the Consecon Quarry, to the west of Mountain View (Figure 2 and 3), as being toward the west-northwest. The west-southwest flowing ice could have produced the asymmetrical kink band, however, it does not explain the presence of the upright fold, and both the fold and the kink band die out in an upward direction which would not be the configuration if they were formed by glacial overriding.

Pure shear caused by tectonically induced compressive stresses can produce both upright and asymmetrical folds. As previously reported (McFall and Allam 1990) pop-ups in the Phase I study area occur in the northwest orientation indicating relief of stresses oriented southwest-northeast. Similar orientations

of stress relief features occur in the Roblindale Quarry at Roblin, Ontario, approximately 60 kilometres to the north of the Mountain View Quarry (McKay 1987; McKay and Williams 1989). Other stress relief structures have been observed throughout southern Ontario (White et al. 1974) and stress orientation data for southern Ontario (Lo 1978; Lee 1981) support the presence of a regional stress regime oriented southwest-northeast. The orientation of the brittle structures in the Mountain View Quarry is consistent with the present day stress orientation suggesting that they may have formed recently, or could have formed in response to a similar regional stress orientation that may have been present during an earlier time.

The structures in the Mountain View Quarry are generally parallel to brittle fold structures observed in the Consecon Quarry (McFall and Allam 1990). This similarity in orientation suggests that the two sets of structures were formed under comparable, possibly the same, stress conditions and, therefore, that they may have been formed at the same time. It is, however, necessary to be circumspect when interpreting structures observed in quarries where the bedrock has been blasted and to be aware of the possibility that the disruption of the bedrock may be due to this activity.

5.0 PICTON QUARRY

5.1 INTRODUCTION

The Picton Quarry is located 4 kilometres to the northeast of the town of Picton, on Highway 49, in Sophiasburgh Township, Prince Edward County (UTM 329750E-4879750N) (Figure 2 and 3). Owned and operated by the Lake Ontario Cement Company Ltd. (Derry Mitchener Booth and Wahl and Ontario Geological Survey 1989), the quarry consists of two excavations; one to the southeast of Highway 49, and one to the northwest of the highway. The southeast excavation is larger and extends 55 metres into the bedrock to expose both the Lindsay and Verulam Formations in cross-section. The northwest excavation is smaller and exposes about 20 metres of the Lindsay Formation.

The Lindsay Formation consists of medium-bedded limestones that are commonly separated by very thin, undulating shale partings which impart a nodular texture. The Verulam Formation is composed of interbedded limestones and shales.

5.2 DESCRIPTION OF STRUCTURES

The central part of the southeastern excavation is cut by a 40 metre wide zone of very closely spaced fractures that includes faults, veins of calcite, and an ultra-mafic dyke. In the northwestern excavation, the same zone of closely spaced fractures is about 100 metres wide. In both, the fractures are well developed, but widely spaced on either side of the zone. A total of one hundred and ten fracture orientations was measured for both excavations. Equal-area net, lower hemisphere plots of the fracture data indicate that fractures are oriented mostly in the 086°/77°[1] and 300°/88°[1] directions (Figure 20, Appendix A).

5.2.1 Ultramafic Dyke

An ultramafic dyke intrudes the Ordovician strata and is exposed in both parts of the quarry. The dyke is heterogeneous with a coarse grained central region and a fine-grained marginal zone, although a coarser-grained marginal zone was observed at some places but is not common. The dyke includes fragments of limestone, has numerous stringers, and in places is fractured. Barnett et al. (1984) gave a detailed description of the petrography and mineralogy of the dyke. In summary, Barnett et al. indicated that the dyke is composed of olivine or

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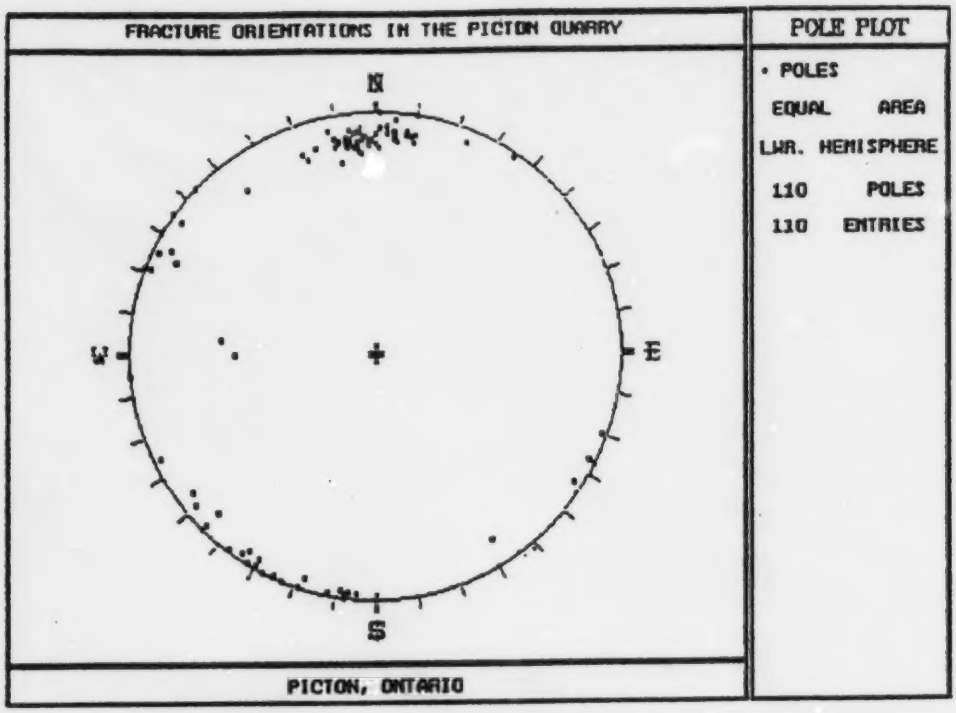
[1] Right hand rule.



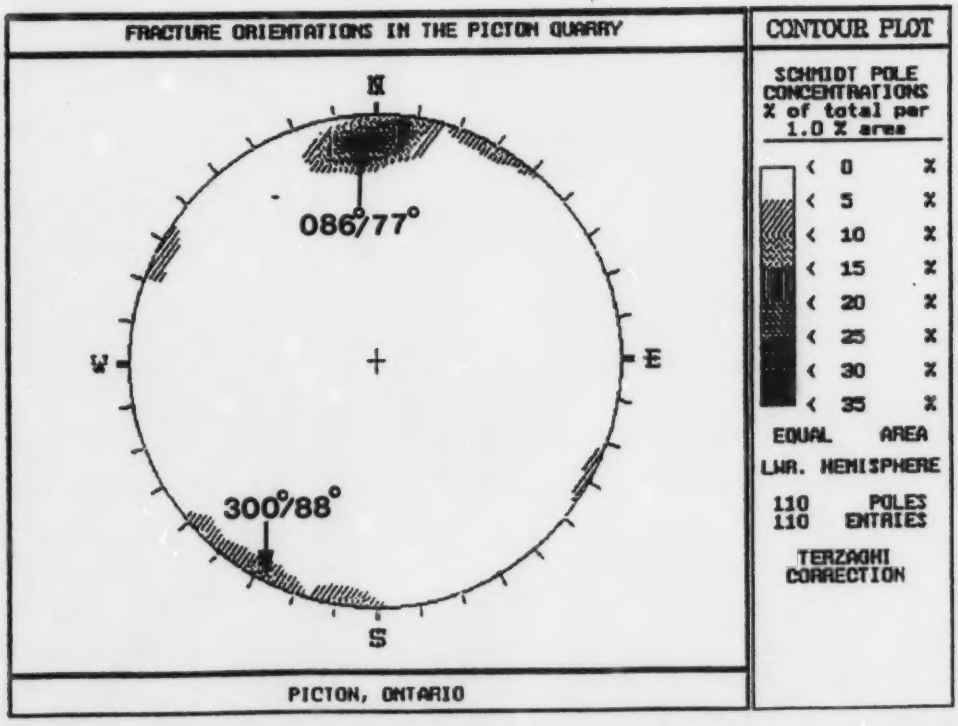


Figure 20: Fracture orientations, Picton Quarry, Prince Edward County.

serpentinized pseudomorphs after olivine and rare phlogopite phenocrysts set in a ground mass of phlogopite, perovskite, chlorite, acicular apatite and blocky spinels. Barnett et al. (1984) also suggested that several phases of injection had occurred.

In the southeast excavation, the dyke intrudes a 125 centimetre wide zone of intensely fractured limestone. The dyke is 32 centimetres wide and trends 090°/76°[1] (Figure 21) and is fractured. Calcite is commonly observed infilling the fractures in the limestone near the dyke, and less commonly as small lenses or stringers cutting the dyke rock. Sub-horizontal slickenlines can be observed both on the fractures in the limestone and on the dyke rock. Bowlby (1986) noted slickenlines on fractures within that part of the dyke that was exposed on the second lift.

In the northwestern excavation, the dyke is well exposed on the wall of the upper lift, but only poorly exposed on the lower lift walls and floor of the quarry. The zone of intense fracturing which hosts the dyke, however, is present and prominently marked.

Barnett et al. (1984) conducted palaeomagnetic and K-Ar age-dating studies on the dyke rock and concluded that intrusion occurred in the Jurassic (173 Ma) during reactivation of basement structures that may have served as conduits for deep seated magmatism. They suggest that the reactivation was probably a

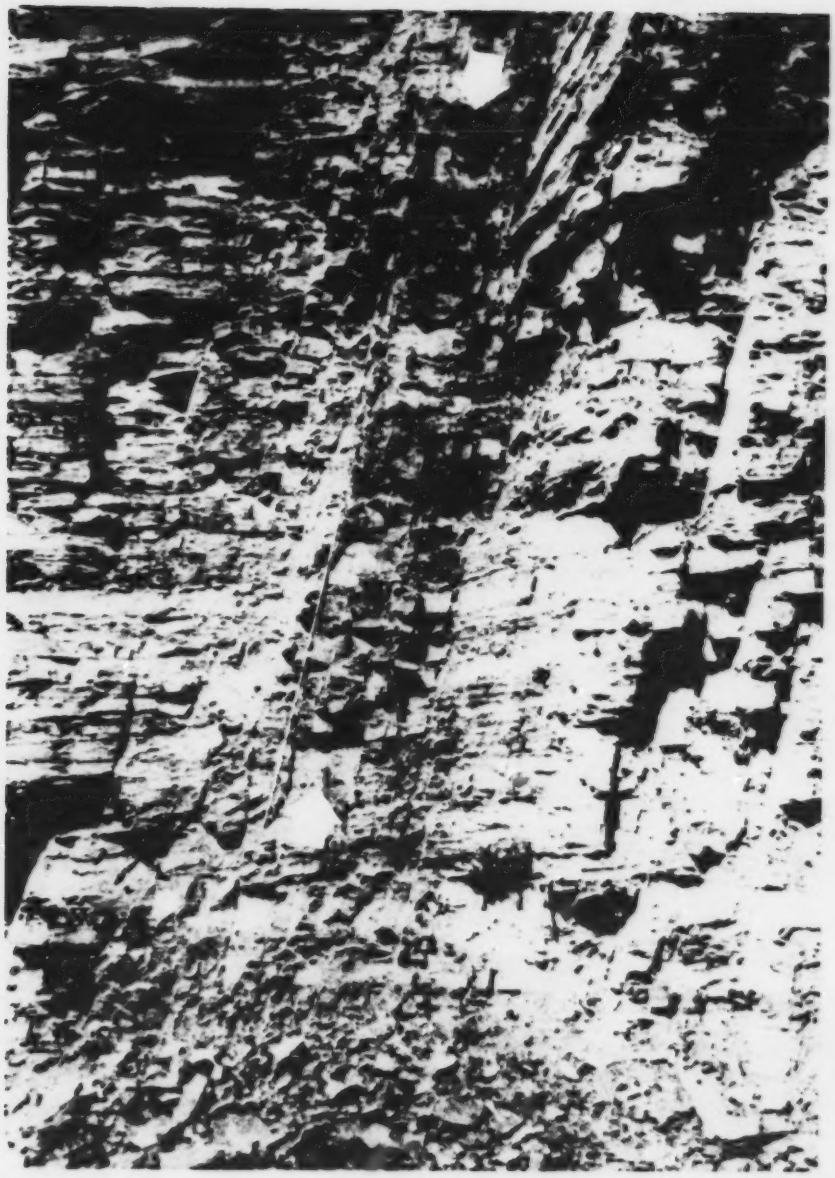


Figure 21: Highly fractured zone containing ultramafic dike of Jurassic age, Picton Quarry. Dyke is denoted by arrows. Scale is 1.8 metres long.

distal expression of continental rifting prior to the opening of the North Atlantic.

5.2.2 Fault

A large fault trending 238°/78°[1] is exposed in the walls of the lowest lift of the southeastern excavation and appears to transect the dyke (Figure 22). At the floor of the quarry, the fault vertically offsets the strata by about 20 centimetres. The amount of separation decreases to almost zero about 10 metres above the quarry floor. The fault is sinuous, both vertically and horizontally, and appears to splay into several limbs as it approaches the fracture zone hosting the ultra-mafic dyke. Each of the fault limbs is marked by calcite infilling. Prominent, sub-horizontal slickenlines, which indicate strike-slip movement, were observed on the fault surfaces. Although the fault appears to intersect the ultra-mafic dyke, it is not known whether the dyke or the fault is displaced as the area of their intersection is presently not exposed.

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[1] Right hand rule.

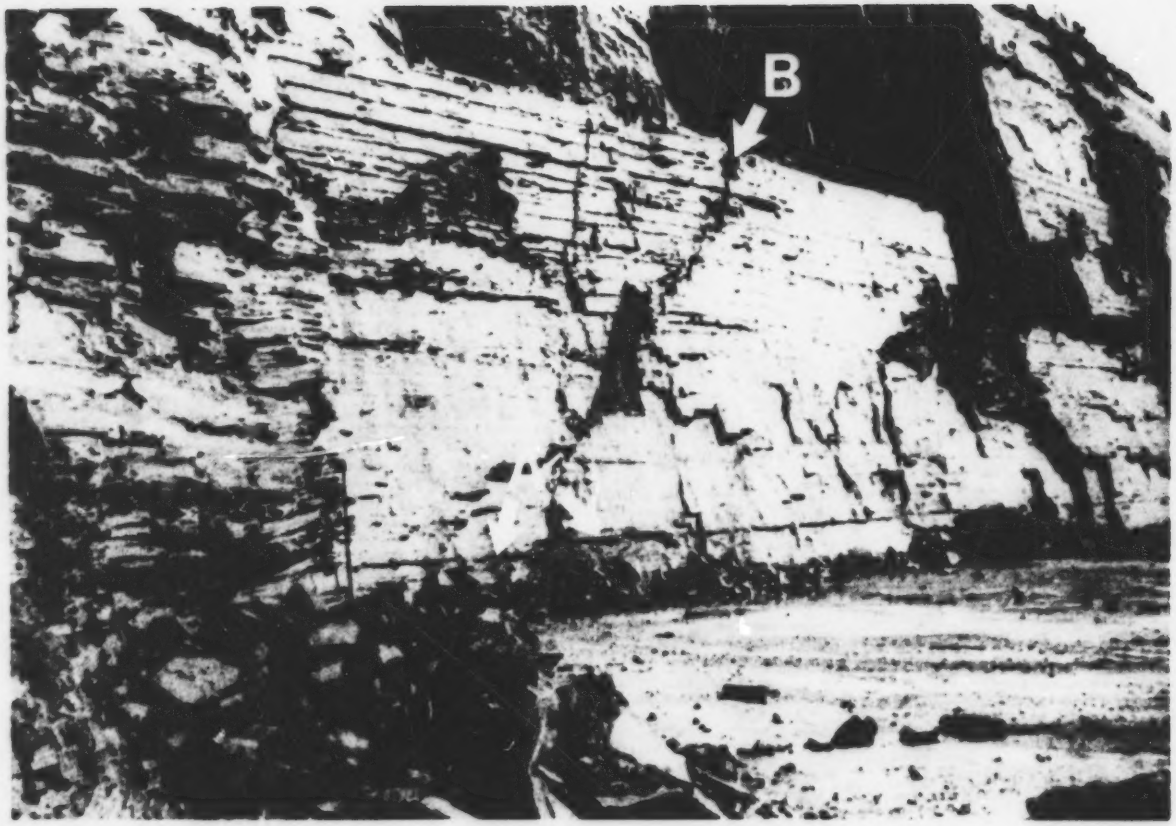

Figure 22: Fault in the Picton Quarry. Thin shale layer (A) is offset across a fracture (B) with sub-horizontal slickensided surfaces.

5.3 DISCUSSION

The presence of an ultramafic dyke of Jurassic age has important implications in the interpretation of the tectonic history of the area.

Firstly, the presence of the dyke indicates that the fault, and possibly others in the surrounding area, either formed or was reactivated during the Jurassic. It also firmly establishes the age of the reactivation.

Secondly, the observation of sub-horizontal slickenlines on fractures in the dyke rock indicates the possibility of post-emplacement faulting with strike-slip movement. It is possible that the fractures in the dyke rock are the result of cooling, but this does not preclude the possibility of their later re-activation. A study by Manning and de Boer (1989) of 235 Mesozoic dykes in the New England area of the United States showed that slickensided fractures were observed in about half of the dykes they examined. They indicated that of the slickensided fractures, 80% were cooling joints that were reused during postcooling deformational events and 20% were true faults which also cut the country rock. They concluded: a) that cooling fractures can provide a locus for later deformation and b) that a post-cooling deformational event did occur in at least the New England region. Their findings help support the argument that a

period of structural instability may have occurred in the Prince Edward County region later than the Jurassic. The exact timing of this instability is presently unknown. It is hoped that further work will give a possible age for this later deformation.

Thirdly, the composition of the Picton dyke, and a similar dyke occurring at Varty Lake (Barnett et al. 1984) on the northwest side of the Picton-Napanee Fault, suggests that at least part of the fault system may possibly extend to the base of the crust.

Fourthly, the suggestion by Barnett et al. (1984) that the dyke was emplaced in conjunction with deep seated magmatism probably related to the tectonic event of continental rifting prior to the opening of the North Atlantic supports the possibility that distal tectonic events can, and do, affect the stability of the intra-plate environment. Work by Sanford et al. (1985) in southwestern Ontario also corroborates this concept.

Finally, the Picton Fault appears to be part of a much more extensive fault system that extends from the southern part of Lake Ontario near Rochester, New York, north-northeast through Prince Edward County and the Paleozoic rocks and the Precambrian terranes north of the county to as far as the Ottawa-Bonnechere Graben, a distance of over 200 kilometres (Figure 6). Both the Frontenac-Sharbot Lake Terrane Boundary and Rideau Fault exhibit some indications of movement during the post-Frontenac Terrane assembly period (900 Ma) (Easton 1988; R.M. Easton, personal communication 1990). As yet, no evidence of Phanerozoic movement

along these structures has been observed within the Precambrian exposures. In the Paleozoic rocks, the southwest extension of the fault and terrane boundary a) cuts the Middle Ordovician rocks, indicating post-Middle Ordovician reactivation, and b) has associated ultra-mafic dykes at Picton and Varty Lake (Barnett et al. 1984) that are indicative of at least Jurassic age reactivation. From this it can be interpreted that the Precambrian fault and terrane boundary system may have been subjected to at least two periods of reactivation. It further implies that not all faults and terrain boundaries in the Precambrian, be they exposed or beneath the Paleozoic cover, ceased to be active at the close of the Precambrian era. It is conceivable that only part of the fault system has been reactivated. If so, then the controls on the extension of reactivation along the length of the fault are unknown. This is an area where considerably more work is needed.

Given the large number of faults that have been mapped within the Precambrian terranes, and those that probably occur beneath the Paleozoic and Mesozoic cover, the reactivation of Precambrian faults during Phanerozoic time is important in the consideration of long term structural stability in Ontario.

6.0 GEOPHYSICAL SURVEYS

6.1 INTRODUCTION

Many of the bedrock structural features scattered throughout the study areas are partially or completely blanketed by Quaternary and Recent deposits making direct observation difficult. Several obscured structural features were examined using shallow refraction seismic techniques. These features include a potential fault and an area of possible folding, or doming, of the strata. Side scan sonar and offshore magnetic surveys were conducted in Lake Ontario and the Bay of Quinte by McQuest Marine Sciences Limited aboard the Monitor V, a vessel which was provided by the Ontario Ministry of the Environment. The purpose of the offshore surveys was to determine and locate the possible presence of pop-ups in the lake bottom and to examine the subaqueous expression and magnetic characteristics of the Picton Fault.

6.2 SIDE SCAN SONAR AND MAGNETIC SURVEYS

Side scan sonar and offshore magnetic surveys were conducted in two areas (Figure 3). The first area encompasses approximately 10 square kilometres of Lake Ontario to the south of the Phase I study area, and the second area includes Adolphus Reach, Long Reach, and Telegraph Narrows of the Bay of Quinte and the North Channel (Figure 2).

Observations of the lake bottom in both offshore study areas were made using a dual frequency (100/500 KHz) Klein side scan sonar (Model 590) provided by the Hydraulic Investigations Section of Ontario Hydro. Five traverses were made across the eastern arm of the Picton fault where it extends into Lake Ontario at Point Petre. Three east-west traverses were made from Point Petre to just beyond the Gull Bar (Figure 2). Single traverses were made along Adolphus Reach, Long Reach and Telegraph Narrows with perpendicular lines located at the northeast end of Long Reach and near the junction of Long Reach and Adolphus Reach.

Magnetic surveys, conducted in conjunction with the side-scan sonar surveys, used a Barringer SM 123 Magnetometer that was towed about 40 metres behind the vessel.

6.3 SEISMIC REFRACTION SURVEYS

The shallow seismic refraction method was used at sites in the Phase I study area to determine the vibrational characteristics of the different underground layers, the depths of the layer interfaces and their structural configuration. A Geometrics/Nimbus ES-125 single channel enhancement seismograph was used with a 10 pound sledge hammer and strike plate as a seismic energy source.

Geophysical studies were conducted in two areas: the first at the southern end of King's Crossroad and the second adjacent to the Brewer Nursing Home road (Figure 23).

The presence of a structure extending east-northeastward from UTM 324250E-4859400N to UTM 327550E-4861300N is suggested by the co-linearity of: 1) the southeastern shoreline of Salmon Point, 2) the abrupt linear termination of the Soup Harbour swamp, 3) a gentle 1.2 metre change in elevation of the bedrock surface, and 4) a change in the general character of the eastern arm of the Picton Fault from swampy treed land to generally well drained farm and pasture land. The possible presence of a fault was tested with a survey line along King's Crossroad at UTM 326900E-4860800N, and perpendicular to the possible structure.

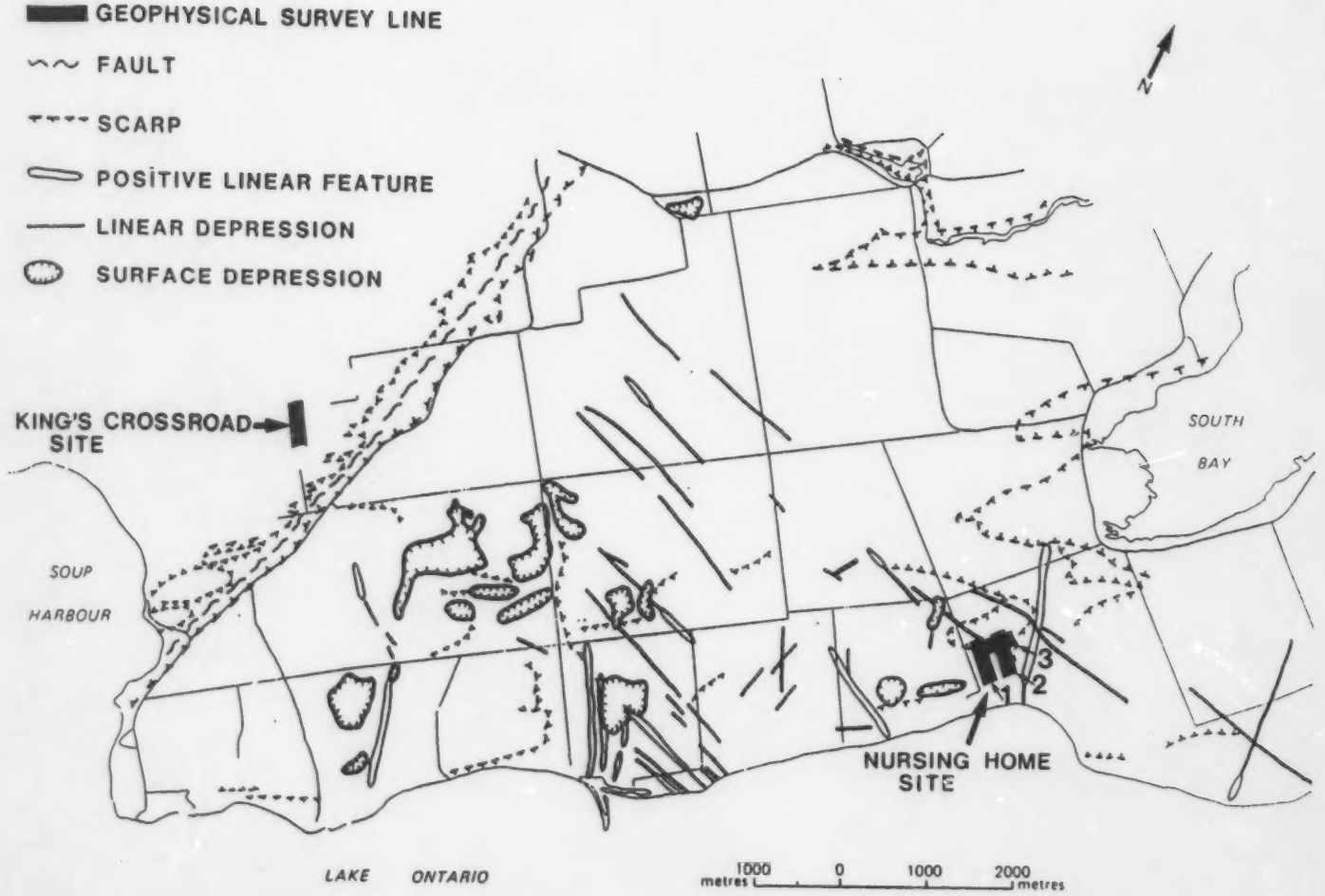

Figure 23: Location of refraction seismic surveys, Prince Edward County Phase I study area (Geology by G. Gorrell and G. McFall).

Semi-circular structures, suggestive of folds or domes, are observed on 1;10 000 false-colour infrared aerial photographs of the eastern part of the Phase I study area (Figure 23). These apparent structures occupy an area of approximately 60 000 square metres centred around UTM 335100E-4861750N. Alternating vegetational types enhance the impression of folded strata. Preferential erosion and deeper weathering of the more shaly and nodular limestone beds, thereby forming slight depressions in the bedrock surface, is suggested. In contrast, the more crystalline beds would not be as deeply weathered and thus would form the topographic highs. Field verification confirmed that the topographically higher parts were vegetated primarily by cedars and that the ground surface was covered with limestone clasts with little or no soil to support grass and weeds. The topographically lower parts commonly had thick soil cover, were marshy, and tended to be densely vegetated by swamp type vegetation or grasses with very few trees.

Two possible interpretations of the circular configuration were being tested by the geophysical surveys. The first attributes the circular traces to folding or doming of the bedrock. The second, relates the configuration to "topographic effect" being superimposed on the very gently dipping beds thereby giving the illusion of folding or doming of the bedrock.

Transverse and longitudinal geophysical transects were conducted across the possible fold traces in order to test the subsurface structure that may be present.

6.4 PRELIMINARY RESULTS AND INTERPRETATIONS

6.4.1 Offshore Side Scan Sonar and Magnetic Surveys

The following descriptions are very preliminary in nature and are based on direct observations of the side scan sonar records and the magnetometer survey data. A more complete analysis of the data will be forthcoming in a report by McQuest Marine Sciences Limited (McMillan and Keyes, in preparation) scheduled for completion in 1990.

Offshore, as on land, the eastern arm of the Picton Fault occupies a broad, sediment infilled valley bounded by bedrock outcrops on either side. The presence of pop-ups in the offshore region was confirmed. Records from traverses approximately parallel to the southeast shoreline show two, possibly more, pop-ups that are co-linear with those documented on land (McFall et al. 1988; McFall and Allam 1990).

Very large magnetic anomalies were measured along the southern shoreline of the Phase I study area, just west of, and less than 1 kilometre offshore from the Gull Bar (UTM 331900E-4858150N) (Figure 2 and 3). Large magnetic anomalies were also present at the northeastern end of Long Reach. The results of this survey should be compared to results of airborne magnetic surveys published by the Geological Survey of Canada (GSC Map

7333G), and the regional geology to determine the implication of these anomalies.

6.4.2 King's Crossroad

The preliminary interpretation of the data resulting from the seismic refraction profile along King's Crossroad is illustrated in Figure 24. Generally, three seismic velocity layers are present: 400-600 m/s, 2200-2500 m/s, and 3600-5000 m/s. The second velocity layer appears thicker on the south half of the section. In the centre part of the section, which is approximately where the proposed fault would be located, the second velocity layer pinches out against an abrupt rise in the elevation of the third velocity layer, then continues northward at a higher elevation than on the south side of the rise. Not prominent on the section is a gentle dip in the topography that marks the possible location of the proposed fault. One possible interpretation of this configuration is a more fractured zone, which would permit deeper penetration of weathering, to the south of centre. Possible displacement of the more rigid bedrock across this fracture zone is suggestive of faulting. To confirm the interpretation of a fractured zone, and or faulting, resistivity exploration techniques coupled with a deeper seismic survey would be required across the same profile.

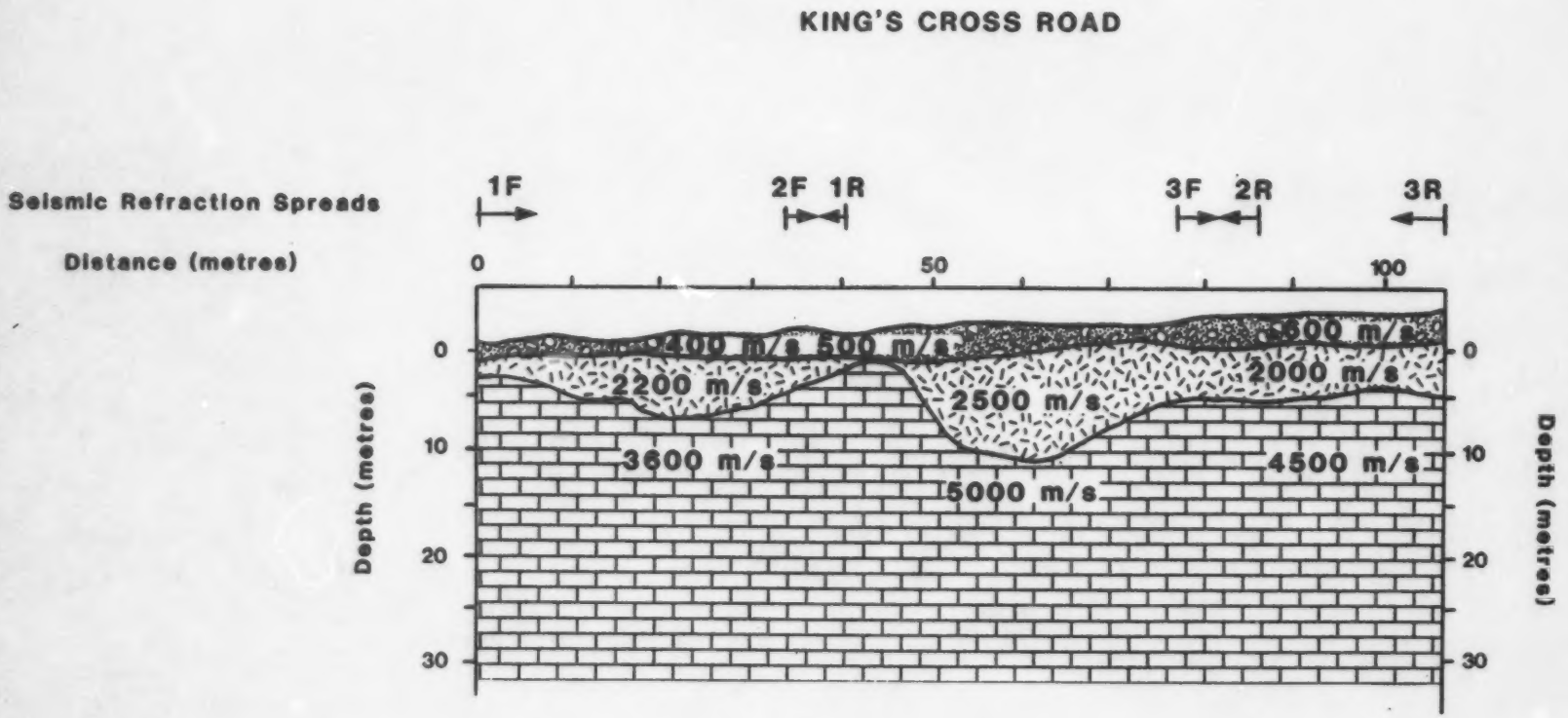

Figure 24: Refraction seismic, synthetic cross-section, King's Cross Road, Prince Edward County Phase I study area.

6.4.3 Brewer Nursing Home Road

Four survey lines were made; two perpendicular and two parallel to the inferred axis of the fold-like structures being investigated (Figure 23). Generally, the three velocity layers that were determined are: 550-1100 m/s, 2000-3100 m/s, and 4500-5900 m/s (see Appendix B). The upper velocity layer is relatively uniform in thickness. The thickness of the second velocity layer is very irregular possibly indicating either a deeper weathering, or fracturing, of the bedrock in the thicker areas.

Illustrated in the synthetic section for site 1 (see Appendix B), the top of the third velocity layer is generally higher on the north end of the section than on the south and supports a non-structural interpretation for the circular structures. For site 2 (see Appendix B), the top of the third velocity layer dips away from the central part of the section and thus supports the folding or doming concept. The synthetic section for site 3 (see Appendix B) has a zigzag configuration of the top of the third velocity layer. This seismic profile, as is the profile for site 4 (see Appendix B), was located parallel to the possible axis of the folds. Unless the folds plunge at a steep angle, relatively flat-lying layers of regular thickness, similar to the velocity layers illustrated by synthetic section for site 4, would be expected.

As the interpretation of each of the seismic lines appear to be contradictory, the results of these geophysical investigations are inconclusive. If one assumes that the irregularity in the thickness of the second velocity layer is due to the presence of fractures, then perhaps some of the disparities can be rationalized. The presence of fractures cannot be determined by seismic methods alone, thus additional work using resistivity exploration and deeper seismic profiling is required before a more plausible explanation can be determined.

7.0 SUMMARY OF PHASE II

A variety of activities were conducted in the Prince Edward County study areas by the Ontario Geological Survey in 1989. These focused on the detailed examination of bedrock structures in the area, such as faults and open fractures, in order to determine their subsurface characteristics and to evaluate the possible age of formation or of last movement of the feature. The activities included: detailed mapping of bedrock structures exposed in the Mountain View and Picton quarries and along the north shoreline of Long Point; seismic refraction studies of possible faults and folds occurring in the Phase I study area; and side scan sonar and magnetic surveys of the Picton Fault and pop-ups in the offshore region.

The regional structural framework of east-central Ontario has been revised to include Precambrian structural features. The regional fault system consists of the Clarendon-Linden Fault System that extends across Lake Ontario from western New York State, the assumed Salmon River Fault and the Picton/Napanee faults that cut the Paleozoic terranes, and the Rideau Fault and the Frontenac-Sharbot Lake Terrane Boundary zone in the Precambrian rocks of east-central Ontario. Low magnitude earthquakes, in Prince Edward County, and intermediate magnitude

earthquakes, in western New York, either on or adjacent to this regional structure suggest the possibility that the structure is seismogenic.

Detailed mapping was undertaken of the bedrock structures exposed by 10 to 15 metre high cliffs along the north shoreline of Long Point and in the Mountain View and Picton quarries. Large open fractures, observed in the Phase I study area, were not common in the cliff exposures. Those fractures that were open more than a few millimetres, and to a depth of 10 metres, were generally associated with faults. Three normal faults and a sub-parallel, conjugate pair of low angle reverse faults were documented. Ductile deformation, in the form of drag folds, is associated with at least two of these faults. Two zones of highly fractured bedrock were observed to host strike-slip faults that trend east-west and were partially infilled with euhedral calcite. Brittle deformation, in the form of northwest trending folds, was observed in the Mountain View Quarry. Like the folds observed in the Consecon Quarry during the 1988 field studies, it is highly unlikely that these folds were formed by "glacial shove". In the Picton Quarry, an ultramafic dyke of Jurassic age intrudes a highly fractured zone that trends east-west. The dyke may be intersected by a strike-slip fault that trends northeast-southwest, however the intersection was not exposed.

Geophysical investigations were conducted in the Phase I study area to test the possible presence of a fault and folding. Large magnetic anomalies were also detected offshore of the Phase

I study area and along Long Reach. Side scan sonar surveys detected northwest trending pop-ups in the floor of Lake Ontario adjacent to where pop-ups were mapped in the Phase I study area. Whether the pop-ups are restricted to a zone and/or what the controls their location, other than possibly pre-existing faults (McFall and Allam 1990), is as yet unknown.

The presence of sub-parallel faults with apparently opposite senses of movement, faults with evidence of two or possibly more periods of movement, and the observation of both ductile and brittle deformation structures suggests that the tectonic history of Prince Edward County is more complex than previously believed and that the area probably has been subjected to several periods of deformational stress. The field observations reported here indicate that periodic rejuvenations of the structures probably occurred between the late Ordovician to some time after the Jurassic but the presence elsewhere in the county of neotectonic features (McFall et al. 1988, 1989) suggests a more recent period of instability. Ongoing stress relief is indicated by the presence of earthquake activity related to some of the major structures which cut the eastern end of Lake Ontario and Prince Edward County (Figure 8) (McFall et al. 1989 and in preparation).

The presence of periodically rejuvenated structures and neotectonic features in southern Ontario has important implications for the construction of engineered structures. A clear understanding of these geological features, the stresses

which formed them and how they may act in the future is a necessary component of proper site evaluation and suitable construction design.

8.0 RECOMMENDATIONS FOR FUTURE WORK

8.1 GEOLOGY

With the exception of reconnaissance mapping in the Long Point area and in the Picton, Mountain View and Consecon quarries, detailed geological mapping of both the Quaternary and bedrock geology has been conducted only within the boundaries of the Phase I study area. The presence of major faults in the area, the occurrence of recent seismicity and apparent linkage with the seismically active Clarendon-Linden Fault in New York State, and the evidence supporting the re-activation of Precambrian faults during the Paleozoic and at least up to Jurassic time, indicates a complex structural and tectonic history for the area. To aid in the reconstruction of the tectonic and neotectonic history of the area, the following additional work is recommended.

1. Aerial photographs of the remainder of Prince Edward County should be examined for the possible presence of additional bedrock structures (such as pop-ups, faults and folds) requiring ground validation and documentation.

2. Reconnaissance surveys to determine the possible presence of pop-ups on land, outside of the study area.

3. Continued field work including: further examination and documentation of bedrock outcrops, particularly those exposing the rocks in cross-section or exhibiting deformation; collection of any materials which could possibly be age dated; and, if possible, attempt to establish a sequence of events or structural deformation history for the area.

4. A preliminary fracture and lineament study of the entire county to determine if the rectilinear pattern observed on Long Point is repeated elsewhere.

5. Investigations of Recent, Quaternary and Paleozoic geology along and adjacent to the assumed fault along the valley of the Salmon River and the Picton Fault System, for the length of the faults, to search for evidence of timing and direction of movement. To include trenching, sampling of bogs and swamps for carbon dating, detailed mapping for possible offset of the Quaternary and Recent sediments or paleosols across the faults.

6. Detailed evaluation of the age and elevation of beaches in the area to explain discrepancies of elevations, ages and numbers of beaches noted by Gorrell (1988).

8.2 GEOPHYSICS

Detailed seismic refraction and resistivity have been conducted on a number of mesoscopic scale structures within the Prince Edward County study area. Preliminary magnetic surveys have been conducted offshore to the southeast of the study area and in the Long Reach/Adolphus Reach area. By comparison to the geological investigations, there has been little work completed on the geophysical aspect of the project. What work that has been accomplished has been very site specific. No regional work has been conducted on the macroscopic faults which cut the county so very little is known about them in terms of depth, characteristics, and vertical and/or lateral displacements.

1. The results of the shipborne magnetic survey should be compared to results of airborne magnetic surveys published by the Geological Survey of Canada (GSC Map 7333G), and the geology of the area, to determine the regional implication of these anomalies.

2. Additional work using resistivity exploration and deeper seismic profiling is required before a more plausible explanation can be determined for some of the structures in the area.

3. Detailed geophysics across the assumed fault along the valley of the Salmon River and Picton Fault System to determine their exact location and depth, and as a preparatory activity for drilling programmes.

4. A Lithoprobe-type, deep seismic test line has been conducted across the Scotch Bonnet Rise. Copies of this information should be procured for study and for inclusion in the final report on the Prince Edward County study.

5. The Jurassic age dyke in the Picton Quarry may be truncated by the Picton Fault, terminate against the fault, be offset by the fault, or may have been emplaced after the last movement of the fault. Geophysical surveys of where the dyke is exposed in the Picton Quarry should be followed by a programme of surveys designed to test the above scenarios. This would include: identification of the western limit of the dyke, whether the dyke extends across Long Reach to the east, and, if no eastern extension is found, traverses parallel to and the length of the Picton Fault to determine

the possible offset of the dyke and the direction and magnitude of displacement.

6. Regional geophysical studies have not been conducted either in the study area or elsewhere within the county. Although maps of total-field aeromagnetic and Bouguer gravity have been published by the GSC, the information displayed by the maps is reconnaissance in scale. Preliminary interpretations of the magnetometer data indicate a need for more area specific surveys using "truckborne" and "shipborne" equipment to produce a more detailed picture of the subsurface structure of both the study area and the rest of the county.

8.3 SIDE SCAN SONAR SURVEYS

Side scan sonar surveys have confirmed the presence of pop-ups in the offshore region of Prince Edward County, however, the total number and distribution of these structures in the offshore regions is not known. Delineation of these additional structures may further the understanding of the structural evolution of the area. Deformation of the lake bottom sediments have been observed in several locations in Lake Ontario that are not necessarily related to major structures. As low magnitude seismic activity appears to be related to the regional structures

that transect Prince Edward County, examination of the sediments overlying the structures could provide a unique opportunity to observe sub-aqueous evidence of recent stress relief phenomena.

1. A systematic side-scan sonar and sub-bottom profile survey of the lake bottom southeast of Prince Edward County to map the distribution and characteristics of pop-ups present. Such a study should extend south as far as the Canada/US border and laterally as far as required to determined whether the distribution of the pop-ups is random, systematic, or confined to a zone such as they are on land. If the latter holds true over the wider area, then consideration must be given to questions such as: is there a control on the location of pop-ups, what is that control, and what limits the deformation to that particular zone and not at other geologically similar areas.

2. Side-sonar surveys and sub-bottom profiling along the traces of the assumed fault along the valley of the Salmon River and Picton Fault System in the offshore areas to check for possible deformation of the recent sediments related to earthquake activity and/or movement of the faults.

8.4 DRILLING

As the contact between the Lindsay and Verulam Formations is gradational, it is difficult to precisely define this contact when attempting to determine anomalies, be they elevation or thickness, in the apparently flat-lying strata. A number of carefully sited, cored boreholes of a depth that will intersect a distinct marker bed, or formation boundary, would provide the necessary stratigraphic information to support the presence of local and regional faulting. Consideration could also be given to angled boreholes that would intersect the faults in question and prove their existence. Boreholes that extend into the Precambrian rocks could provide information on terrane boundaries and possible faults in the basement. This would firmly establish a link between the Paleozoic and younger features observed at surface and the reactivation of these older structures.

The boreholes could also be used for overcoring stress testing and hydrofracture techniques. This information would help to improve the definition of the regional and local stress regime in the Prince Edward County area.

Given the difficulties imposed on some of the geophysical techniques by the velocity inversion between the limestones of the Lindsay and the shaly units of the Verulam, access to rocks below the Lindsay/Verulam contact is needed. A drilling program

could provide open holes down which geophysical equipment can be lowered to below the velocity inversion interface.

1. One, or more, boreholes to be located to the west of the Salmon River, across from the Roblindale Quarry, to test for the amount of vertical offset of the Ordovician strata across the assumed fault and to test the lithology of the underlying Precambrian rocks. Core should be recovered for stratigraphic analysis, and the holes could be used for stress testing and down-hole geophysics.

2. Angled boreholes could be drilled to intersect the regional and local fault(s) so the suspected fault zone(s) can be observed for the possible presence of mineral infillings, material for age dating, gouge, and slickensides. A borehole was drilled into the Picton Fault by Ontario Hydro (Semec and Lukajic 1979; Lukajic and Semec 1980). The core, if still available, from that hole should be re-examined to make similar observations.

8.5 STRESS TESTING

Very little information is available of the "in-situ" stresses and the regional stress regime in the Prince Edward

County and the eastern Lake Ontario region. The nearest location of stress measurements is over 50 kilometres to the north of the study areas, near Roblin, Ontario, where Ontario Hydro has conducted detailed studies in the Roblindale Quarry (McKay 1987; McKay and Williams 1989).

1. Stress testing, using both surface strain gages and overcoring techniques, to record both the magnitude and orientation of stress in the rock would establish local and areal stress regimes for comparison with the regional norm and possibly identify any anomalies.

8.6 SEISMIC MONITORING

Seismicity and the evaluation of seismic risk are primary interests of neotectonic studies. Little data is available on low magnitude seismicity and historic earthquakes in the county. Recent aeromagnetic data, coupled with bathymetric and bottom profiling data, supports the extrapolation of the seismically active Clarendon-Linden Fault System of northern New York State to known and suspected faults in Ontario. Low level seismicity both within the county and on the Clarendon-Linden Fault has occurred within the past three years. Precise location of seismic events in the Prince Edward County area would provide an invaluable indicator of structures that are active and forge the

link between descriptive field analysis and seismic modeling. Seismic monitoring by the Geological Survey of Canada is on a regional scale and uses a cut off point of M3.0. As a result, this data base is too small to aid in the delineation of bedrock structures along which the low magnitude events have occurred in the county.

1. Interviews should be conducted with residents in order to record recent and historic earthquake occurrences. The results of the study should then be cross checked with seismic records and investigations made of other possible sources of earthquake-like phenomena in order to verify the source of the felt motion.

2. A historic record of seismic events could be compiled by investigation of archives in the area, including local and regional newspapers, for reports on or documentation of earthquakes and earthquake-like descriptions.

3. Portable seismographs and microseismic monitoring equipment should be deployed to record the occurrence of both very low and intermediate magnitude earthquakes. In addition to providing information about the regional structures, this would provide a more complete and accurate account of the seismic activity that occurs within the region. Monitoring of the regional faults that extend from the

Clarendon-Linden into Ontario would document low level seismicity and microseismicity originating in the vicinity of the fault, under Lake Ontario, or in New York State.

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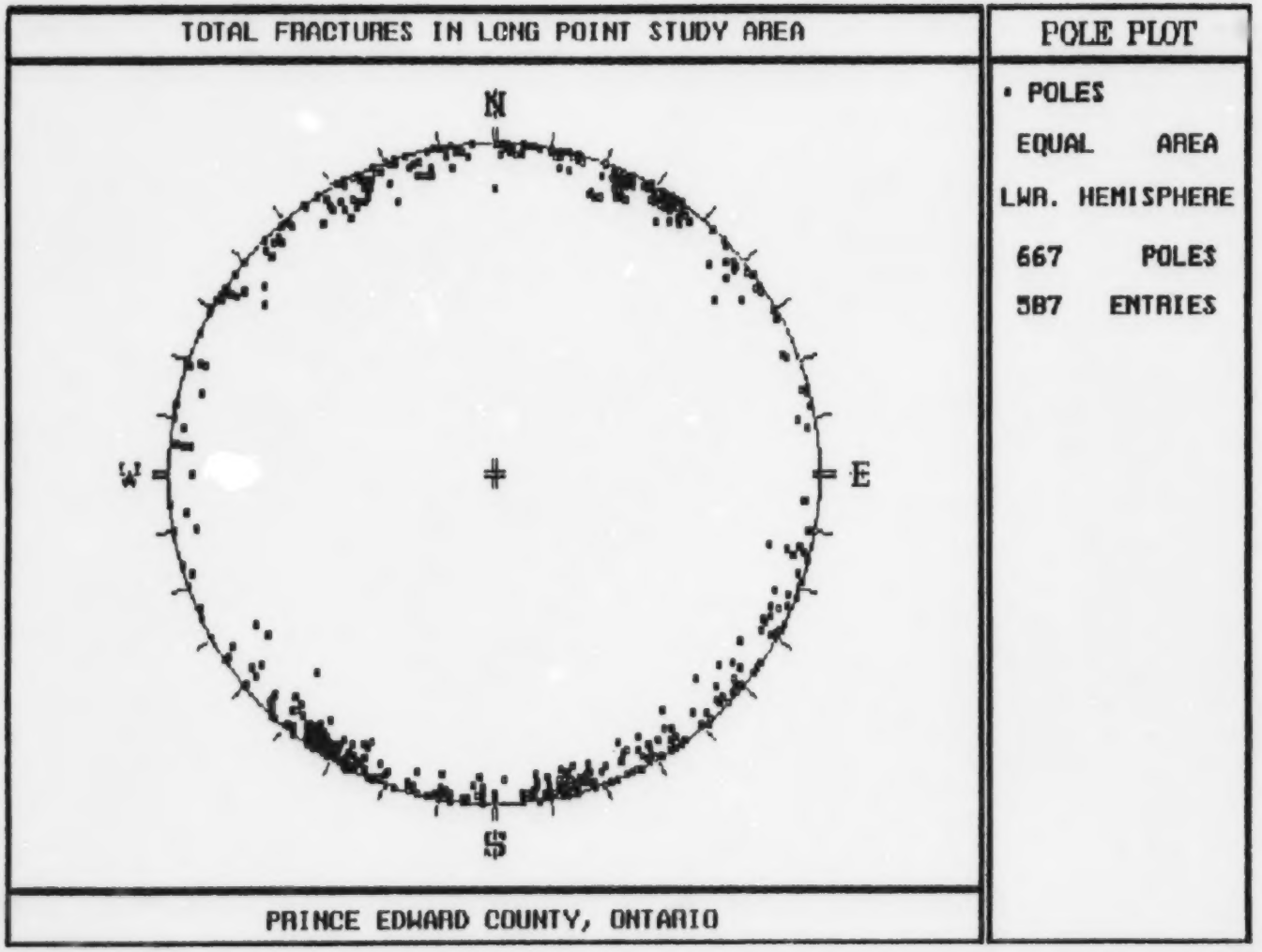
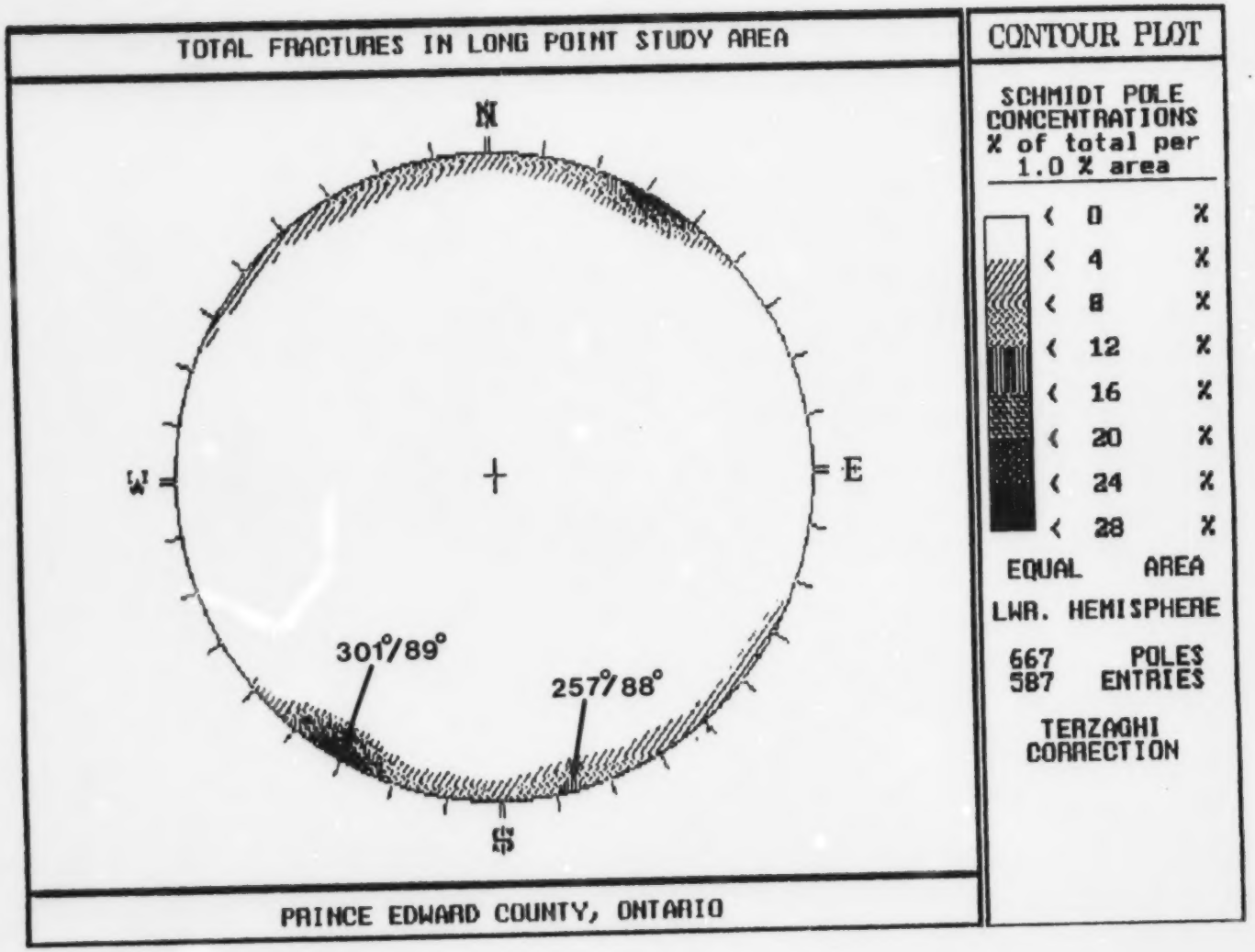
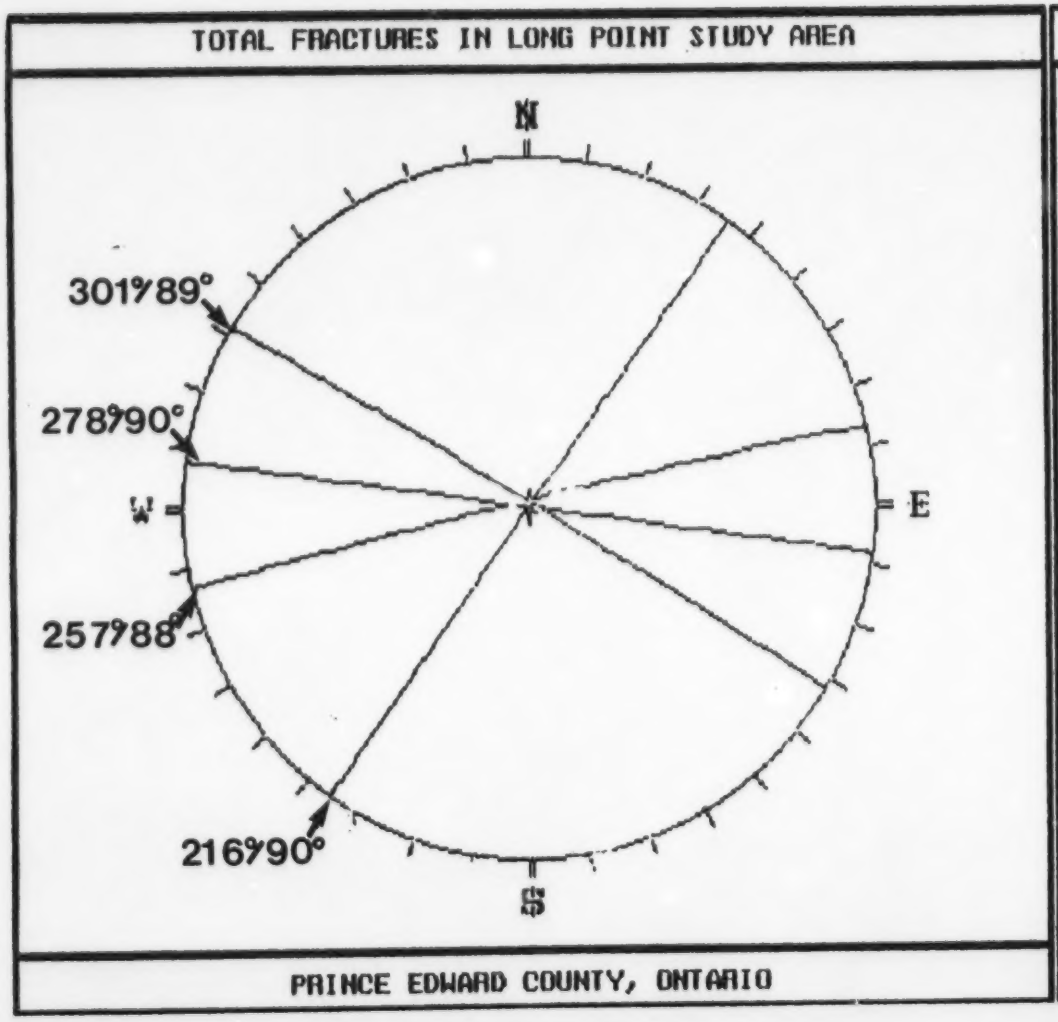
APPENDIX A

Stereonet Plots of Fracture Data

1. Long Point Study Area
2. Mountain View Quarry
3. Picton Quarry


TOTAL FRACTURES IN LONG POINT STUDY AREA
N
W
E
S
PRINCE EDWARD COUNTY, ONTARIO
POLE PLOT
• POLES
EQUAL AREA
LWR. HEMISPHERE
667 POLES
387 ENTRIES


TOTAL FRACTURES IN LONG POINT STUDY AREA
N
E
S
W
301°/89°
257°/88°
PRINCE EDWARD COUNTY, ONTARIO
CONTOUR PLOT
SCHMIDT POLE CONCENTRATIONS
% of total per 1.0 % area
< 0 %
< 4 %
< 8 %
< 12 %
< 16 %
< 20 %
< 24 %
< 28 %
EQUAL AREA
LWR. HEMISPHERE
667 POLES
587 ENTRIES
TERZAGHI CORRECTION

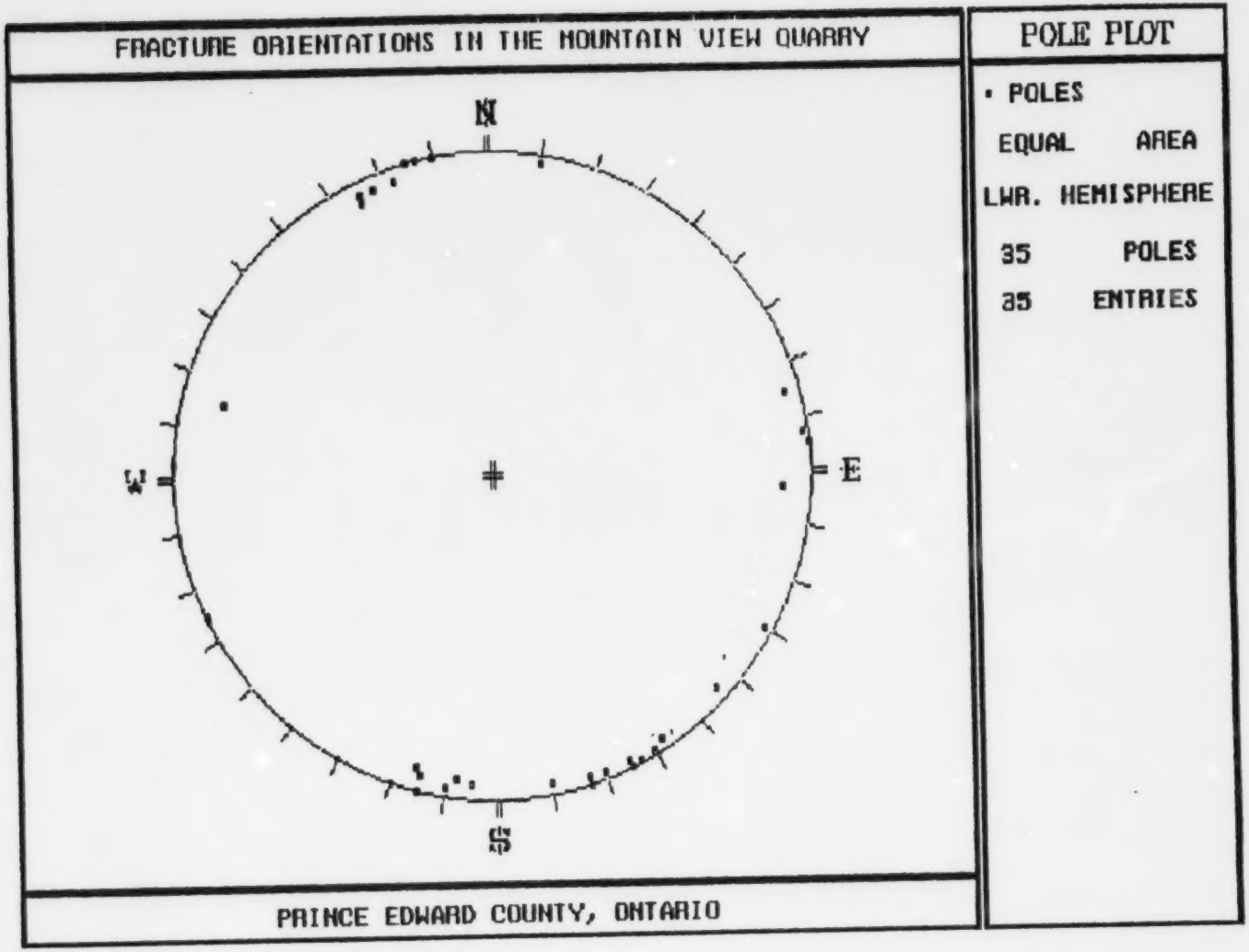


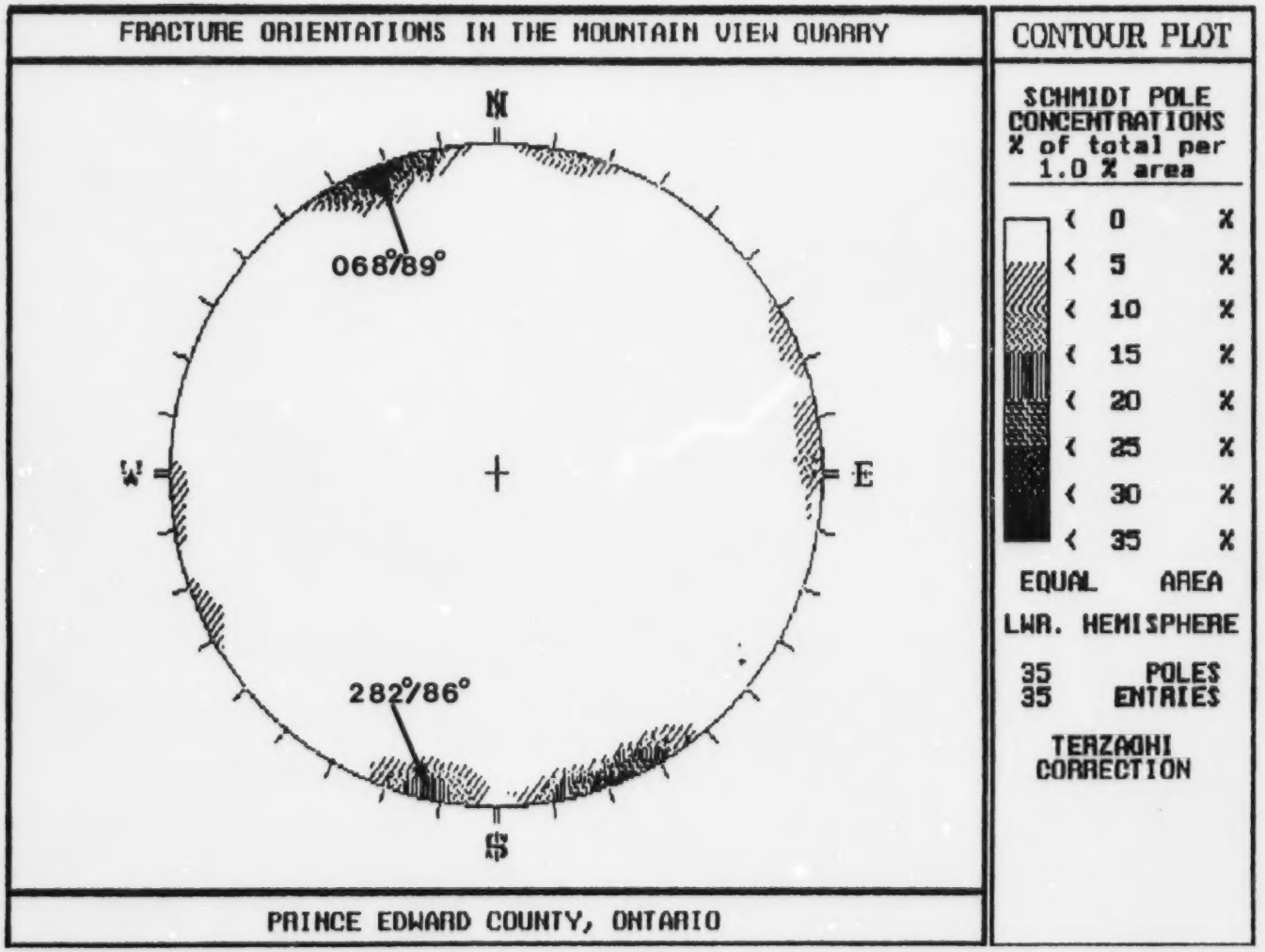
MAJOR PLANES

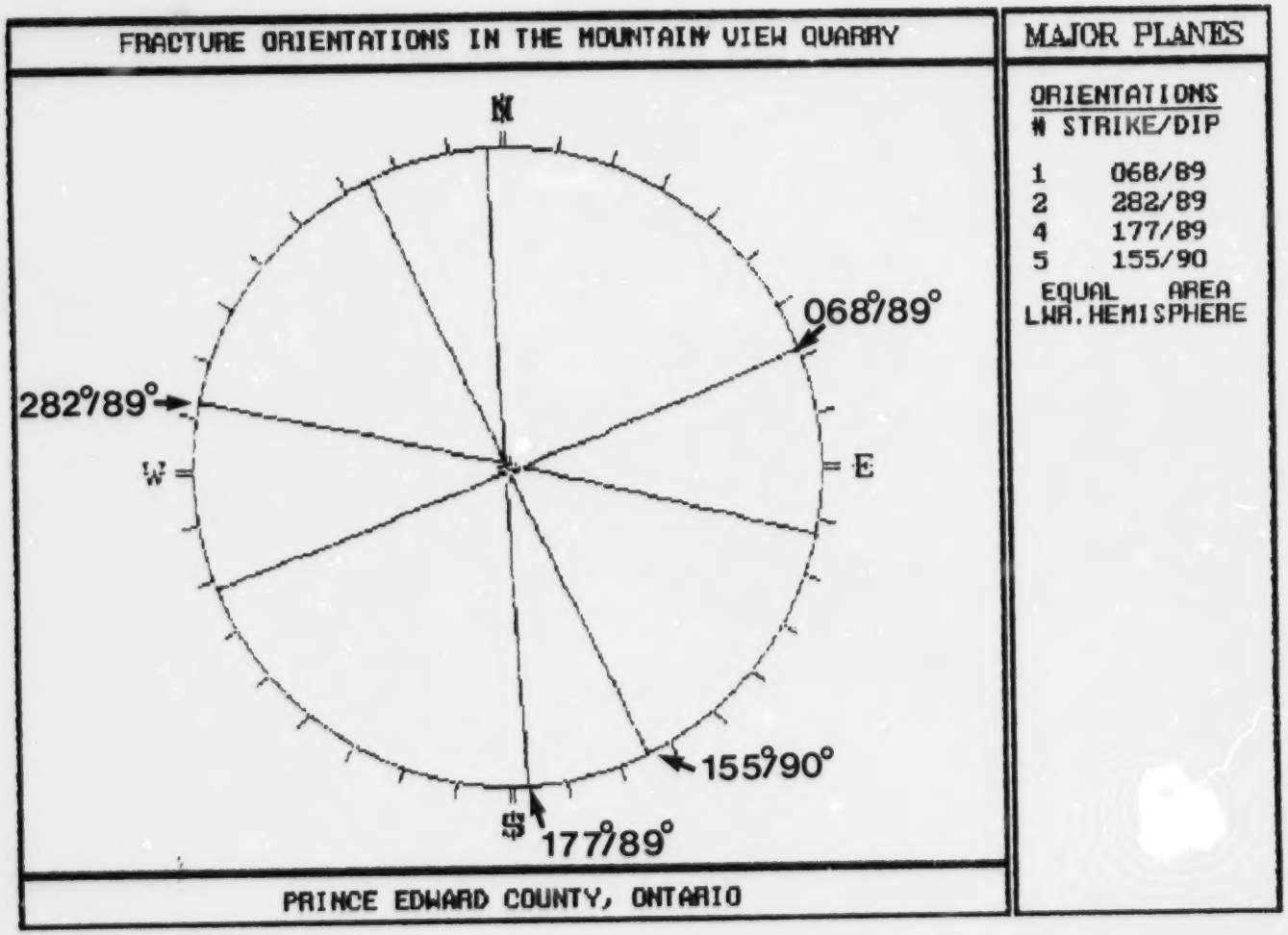
ORIENTATIONS

#	STRIKE/DIP
1	301/89
2	257/88
3	278/90
4	216/90

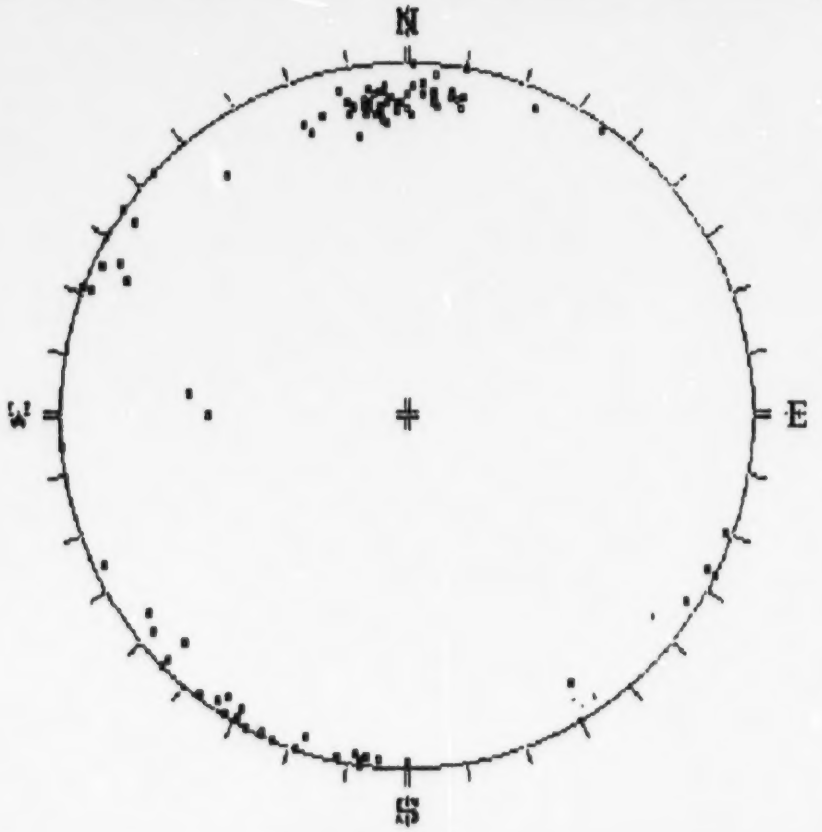
EQUAL AREA
LWR. HEMISPHERE


FRACTURE ORIENTATIONS IN THE MOUNTAIN VIEW QUARRY
N
W
E
S
PRINCE EDWARD COUNTY, ONTARIO
POLE PLOT
• POLES
EQUAL AREA
LWR. HEMISPHERE
35 POLES
35 ENTRIES


FRACTURE ORIENTATIONS IN THE MOUNTAIN VIEW QUARRY
N
068°/89°
W
E
282°/86°
S
PRINCE EDWARD COUNTY, ONTARIO
CONTOUR PLOT
SCHMIDT POLE CONCENTRATIONS
% of total per 1.0 % area
< 0 %
< 5 %
< 10 %
< 15 %
< 20 %
< 25 %
< 30 %
< 35 %
EQUAL AREA
LWR. HEMISPHERE
35 POLES
35 ENTRIES
TERZAGHI CORRECTION


FRACTURE ORIENTATIONS IN THE MOUNTAIN VIEW QUARRY
N
E
S
W
068°/89°
282°/89°
155°/90°
177°/89°
PRINCE EDWARD COUNTY, ONTARIO
MAJOR PLANES
ORIENTATIONS
STRIKE/DIP
1 068/89
2 282/89
4 177/89
5 155/90
EQUAL AREA
LWR. HEMISPHERE

FRACTURE ORIENTATIONS IN THE PICTON QUARRY



PICTON, ONTARIO

POLE PLOT

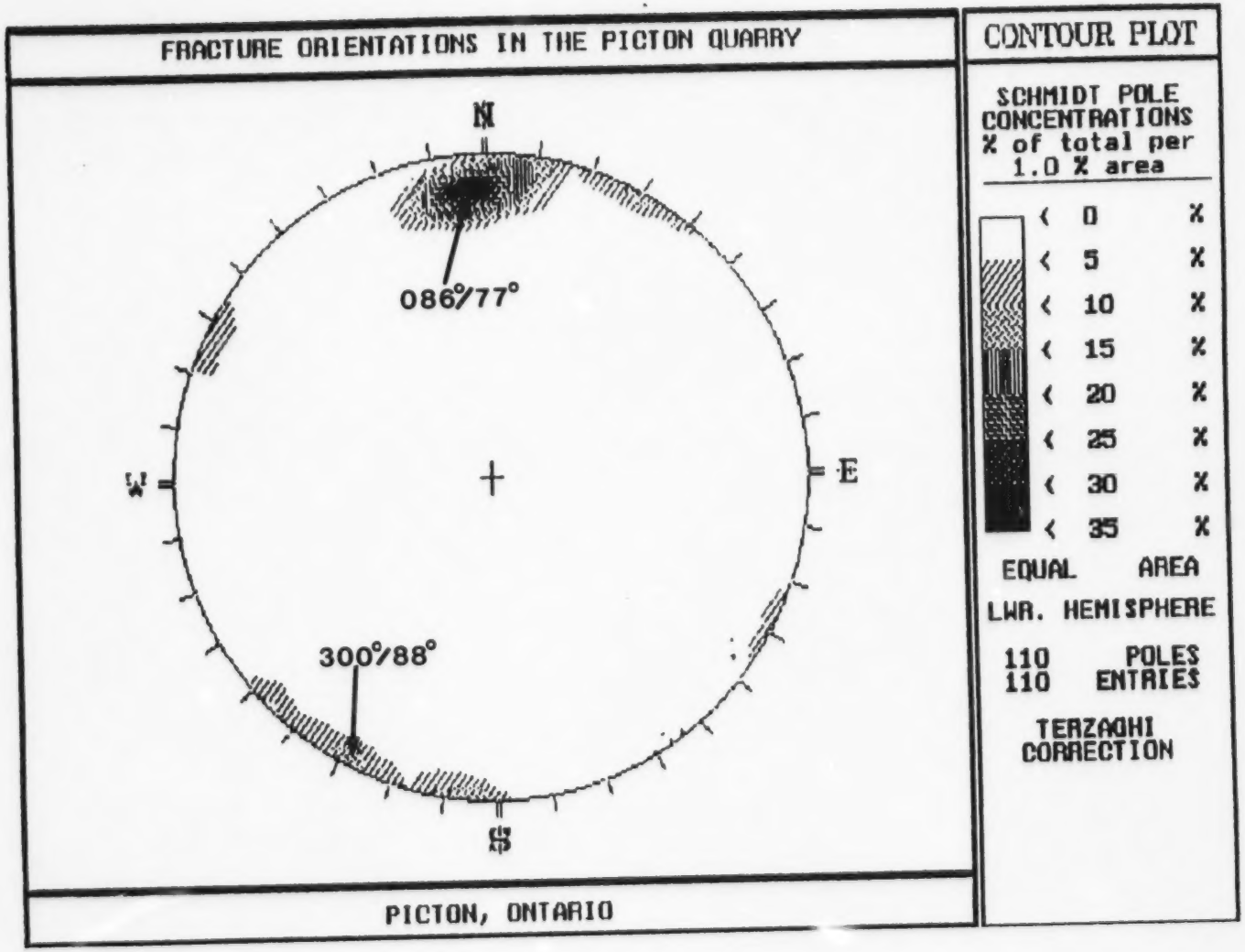
• POLES

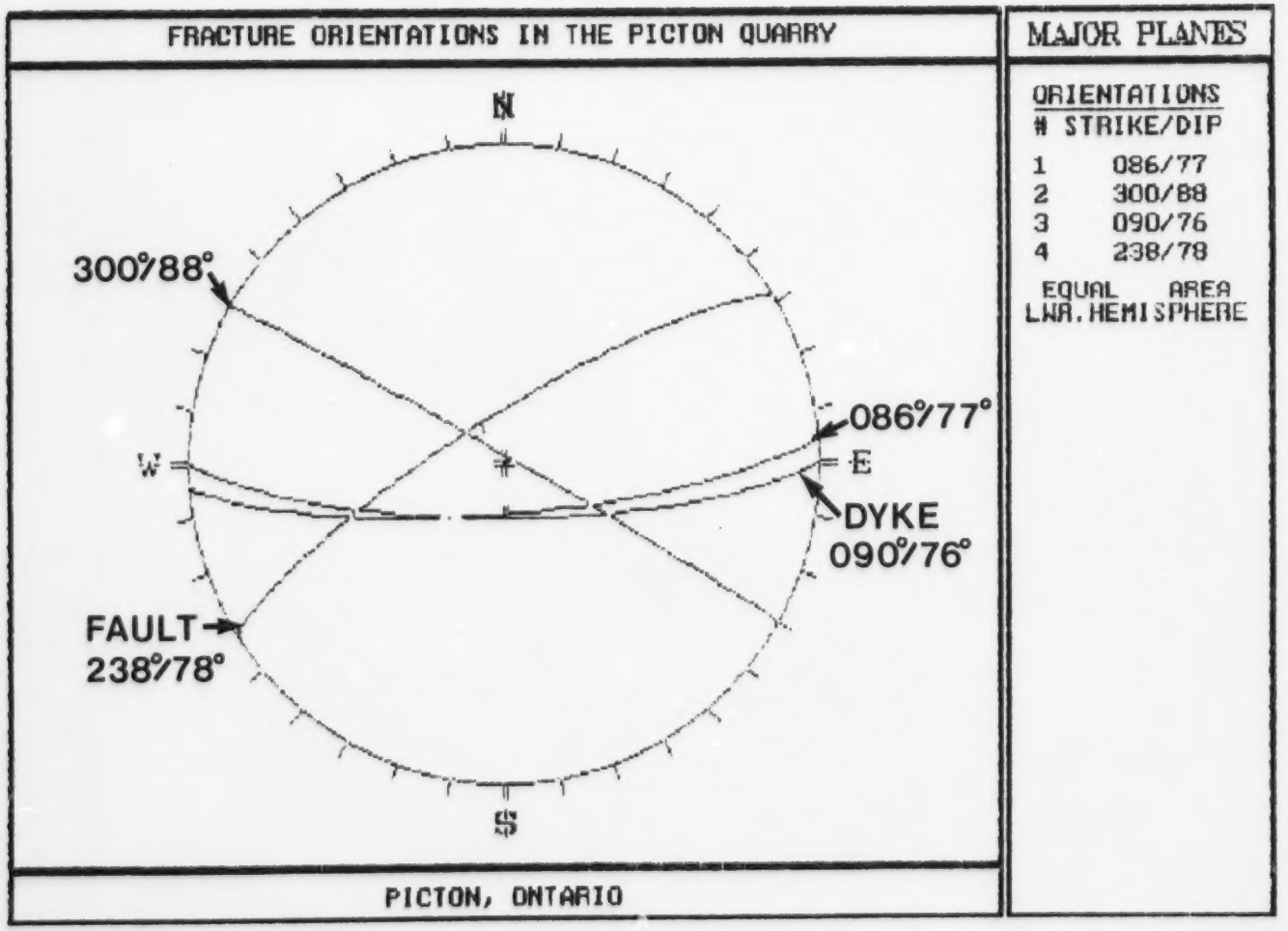
EQUAL AREA

LWR. HEMISPHERE

110 POLES

110 ENTRIES


FRACTURE ORIENTATIONS IN THE PICTON QUARRY
N
E
S
W
086°/77°
300°/88°
PICTON, ONTARIO
CONTOUR PLOT
SCHMIDT POLE CONCENTRATIONS
% of total per 1.0 % area
< 0 %
< 5 %
< 10 %
< 15 %
< 20 %
< 25 %
< 30 %
< 35 %
EQUAL AREA
LWR. HEMISPHERE
110 POLES
110 ENTRIES
TERZAGHI CORRECTION


FRACTURE ORIENTATIONS IN THE PICTON QUARRY
N
300°/88°
086°/77°
W
E
DYKE
090°/76°
FAULT
238°/78°
S
PICTON, ONTARIO
MAJOR PLANES
ORIENTATIONS
STRIKE/DIP
1 086/77
2 300/88
3 090/76
4 238/78
EQUAL AREA
LWR. HEMISPHERE

APPENDIX B

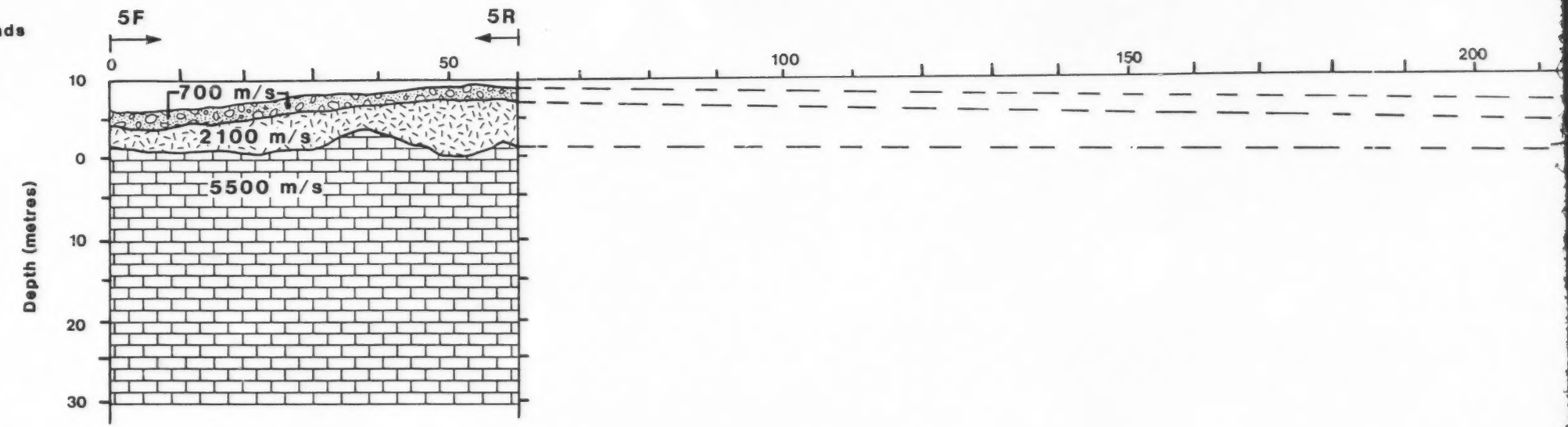
Refraction Seismic Synthetic Cross-sections

Brewer Nursing Home Road Cross-sections

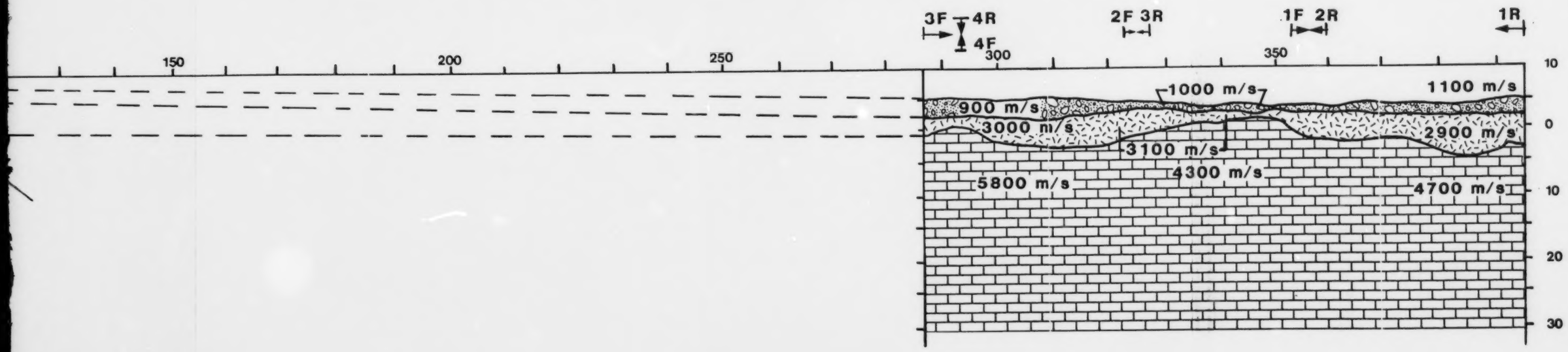
NURSING HOME (SITE

Seismic Refraction Spreads

Distance (metres)



NURSING HOME (SITE I)



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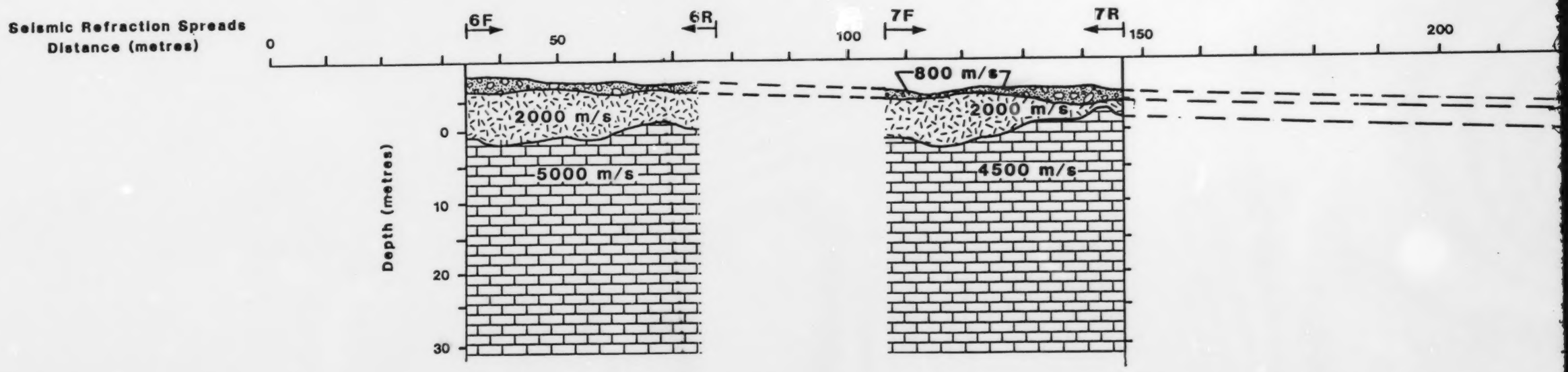

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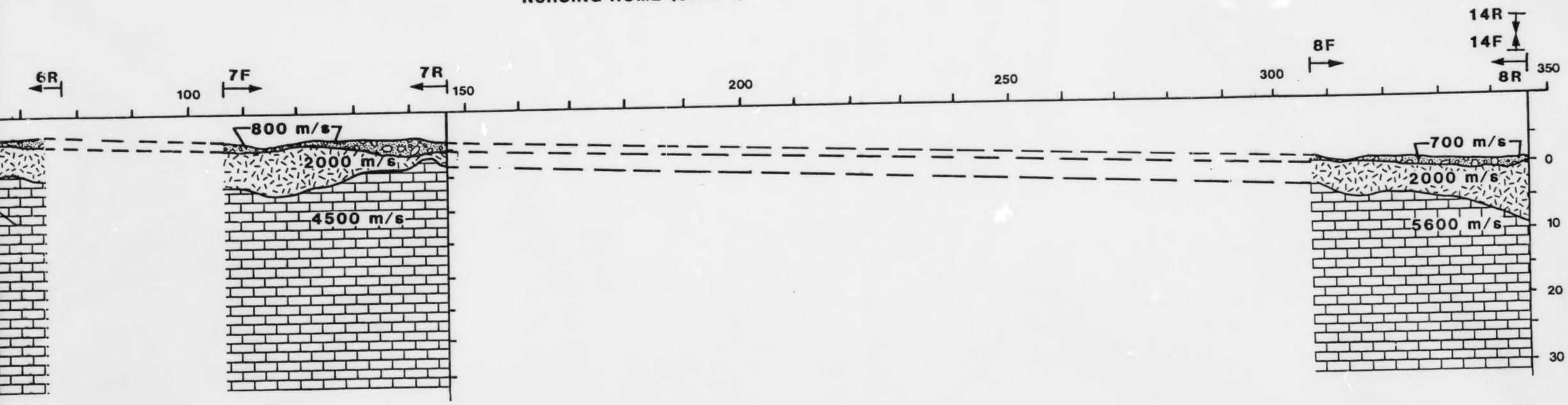

NURSING HOME (SITE III)